

UNITED STATES
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THE EFFECTS OF GROUND WATER, SLOPE STABILITY, AND
SEISMIC HAZARD ON THE STABILITY OF THE SOUTH FORK CASTLE
CREEK BLOCKAGE IN THE MOUNT ST. HELENS AREA, WASHINGTON

By William Meyer, M. A. Sabol, H. X. Glicken, and Barry Voight

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CONVERSION FACTORS AND ABBREVIATIONS

Multiply	By	To obtain
inches (in.)-----	25.4	millimeters (mm)
	2.540	centimeters (cm)
	0.0254	meters (m)
feet (ft)-----	0.3048	meters (m)
miles (mi)-----	1.609	kilometers (km)
square feet (ft ²)-----	0.09294	square meters (m ²)
square miles (mi ²)-----	2.590	square kilometers (km ²)
cubic feet (ft ³)-----	0.02832	cubic meters (m ³)
acre-feet (acre-ft)-----	1233.	cubic meters (m ³)
	0.001233	cubic hectometers (hm ³)
gallons per minute (gal/min)-----	0.06309	liters per second (L/s)
gallons per day (gal/d)-----	3.785	liters per day (L/d)
million gallons per day (Mgal/d)---	3785.0	cubic meters per day (m ³ /d)
feet per second (ft/s)-----	0.3048	meters per second (m/s)
pounds (lb)-----	0.4536	kilograms (kg)
pounds per cubic foot (lb/ft ³)	16.02	kilograms per cubic meter (kg/m ³)
Tons, short, per square foot----- (ton/ft ²)	9765.	kilograms per square meter (kg/m ²)
millimeters (mm)-----	0.03937	inches (in.)
centimeters (cm)-----	0.3937	inches (in.)

acceleration of gravity (g) = 32 feet per second squared,
or 980.665 centimeters per second squared

National Geodetic Vertical Datum of 1929 (NGVD of 1929): A geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called mean sea level. NGVD of 1929 is referred to as sea level in this report.

Tallany, Van Kuren, Gertis, and Thielman Datum of 1981 (TVGT of 1981): Datum derived from reference marks and surveyed at 1-mile intervals by TVGT and from auxiliary elevation control points surveyed by SPAN International, Inc. Specified accuracies were third order for reference marks and to 3 feet for auxiliary points.

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ABSTRACT

South Fork Castle Creek was blocked by the debris avalanche that occurred during the May 18, 1980, eruption of Mount St. Helens, Washington. A lake formed behind the blockage, eventually reaching a volume of approximately 19,000 acre-feet prior to construction of a spillway—a volume sufficiently large to pose a flood hazard of unknown magnitude to downstream areas if the lake were to break out as a result of blockage failure. Breakout of lakes formed in a similar fashion is fairly common and several such events occurring in recent times have posed hazards around the world.

The South Fork Castle Creek blockage consists of poorly sorted, unconsolidated deposits ranging in size from clay and silt to large blocks tens of feet across, with a matrix of predominantly sand and gravel particles. Slopes on the blockage range from about 10 to 41 percent. Physical properties determined from field and laboratory tests suggest that the blockage debris is moderately compact and probably typical of the debris avalanche.

In September 1983 a ground-water mound, 22 feet above lake level, caused flow from the mound to the lake and toward South Castle Creek. Depth to water below the crest of the blockage ranged from 20 to 60 feet. Ground-water levels are expected to fluctuate seasonally and may continue to increase annually until equilibrium is reached. September 1983 water levels are thought to be at their seasonal low and are expected to fluctuate by approximately 15 feet annually.

Analyses of blockage stability included determining the effects of gravitational forces and horizontal forces induced by credible earthquakes from the Mount St. Helens seismic zone, which passes within several miles of the blockage. The blockage is stable at September 1983 water levels under static gravitational forces. If an earthquake with magnitude near 6.0 occurred with September 1983 water levels, movement on the order of 5 feet on both upstream and downstream parts of the blockage over much of its length could potentially occur. If the sliding blocks liquified, retrogressive failure could lead to lake breakout, but this is not considered to be probable.

As ground-water levels increase in the blockage above September 1983 levels, the overall possibility of slope failure on the blockage induced by gravitational and earthquake forces is increased. None of the analyses indicated that initial slope failure on the blockage would result in immediate lake breakout. Retrogressive slope failures could continue to lower the blockage, but lake breakout would eventually occur only if liquefaction of the sliding masses occurs during retrogressive failure. Because this is considered to be unlikely, the possibility of lake breakout as a result of slope failures induced on the blockage by gravitational or earthquake forces is considered to be remote.

The most unstable conditions occur when the blockage is saturated. A 50-foot rise in ground-water levels would saturate most of the blockage. Under this condition, an earthquake near 6.0 magnitude could cause movement of at least several tens of feet on both the upstream and downstream parts of the entire blockage. Factors of safety for slope failure induced by gravitational forces are less than 1.0 over several sections of the blockage when it is fully saturated.

INTRODUCTION

South Fork Castle Creek, a perennial stream draining a 1.3-square-mile area on the northwest flank of Mount St. Helens, was dammed by the debris avalanche that occurred during the May 18, 1980, eruption of Mount St. Helens. (This material is referred in this report as South Fork Castle Creek blockage or, simply, blockage.) A lake began forming directly behind the blockage, and attained a volume of 19,000 acre-feet before its level was stabilized in October 1981 by a spillway constructed through the southeastern edge of the blockage. The volume of water in the lake (now known as South Fork Castle Creek Lake) is believed to be large enough to pose a flood hazard of unknown magnitude to downstream areas if the blockage failed. The blockage could potentially fail because of (1) slope failure induced by gravitational or earthquake forces, (2) liquefaction, (3) piping, and (4) erosion.

This report contains the results of a study to estimate the possibility of slope failure in the blockage from gravitational forces and from horizontal forces induced by earthquake and the effect of ground-water level on these forces. The scope of this study included determining blockage thickness, mapping the geologic units in the blockage, determining material properties of these units, determining ground-water levels in the blockage, and finally, using a digital model to estimate the potential for slope failure in the blockage from static gravitational or earthquake forces.

Formation of lakes because of emplacement of volcanoclastic debris across stream valleys during explosive volcanic eruptions is fairly common, as is the subsequent breakout of these lakes following failure or overtopping of their blockages. Stratigraphic studies by K.M. Scott and R. J. Janda (written commun., 1983) indicate that prehistoric lahars resulting from the breakout of large lakes occurred many times at Mount St. Helens. In modern times, lake breakouts resulting from the failure or overtopping of dams of volcanoclastic debris occurred at Bandai-san Volcano in Japan in 1888 (Knott and Smith, 1890), Katmai Volcano in Alaska in 1912 or 1913 (Hildreth, 1983), and El Chichon Volcano in Mexico in 1982 (Silva and others, 1982).

The techniques used to analyze the stability of the South Fork Castle Creek blockage should be useful in determining the stability of existing dams of volcanoclastic debris or those that may be emplaced in a future explosive volcanic eruption. In addition, they should be applicable to studies of the stability of dams composed of suddenly emplaced, unconsolidated material from large mass movements not associated with a volcanic eruption. The dams formed by the Madison Canyon rockslide of 1959 in Montana (Hadley, 1978), the Lower Gros Ventre slide of 1925 in Wyoming (Voight, 1978), the Mayunmarca rockslide of 1974 in Peru (Kojan and Hutchison, 1978), and the Nevados Huascaran avalanche of 1971 in Peru (Plafker and Ericksen, 1978) are examples of these.

ACKNOWLEDGMENTS

We thank the many people, both inside and outside the U.S. Geological Survey, who helped with the analysis of the stability of the South Fork Castle Creek blockage. Robert Schuster, T. Leslie Youd, and William Smith of the U.S. Geological Survey provided technical guidance in the initial evaluation of potential hazard at the blockage and assistance throughout the project. Craig S. Weaver, geophysicist, U.S. Geological Survey, and Stephen D. Malone, senior research assistant, University of Washington, aided in obtaining information on the seismic history of the study area and the potential for earthquakes to affect the stability of the blockage. The U.S. Army Corps of Engineers extended their cooperation; specifically, Duane Bankofier and Stephen Loren Stockton provided data and pertinent information and Timothy J. Seeman, laboratory work on material properties. Finally, Sunil Sharma of the Purdue University provided guidance in the use of the STABL3 slope-stability model.

GENERAL DESCRIPTION OF THE SOUTH FORK CASTLE CREEK BLOCKAGE

Prior to the May 18, 1980, eruption, South Fork Castle Creek entered Castle Creek about 6 miles from the summit of Mount St. Helens. Material from the debris avalanche blocked South Fork Castle Creek at its junction with Castle Creek, creating South Fork Castle Creek Lake. Castle Creek flowed along the south side of the valley of the North Fork Toutle River and was a tributary of the North Fork Toutle River (fig. 1), joining it 2.2 miles northwest of the site of the blockage.

In its September 1983 condition, South Fork Castle Creek Lake has a surface area of 480 acres, an average depth of 90 feet, and a volume of 19,000 acre-feet. The lake level has been stabilized at an elevation of 2,577 feet by a spillway.

The material blocking the lake comprises poorly sorted unconsolidated deposits ranging in size from clay and silt to large rocks many tens of feet across and some wood debris. The blockage, from ridge to ridge, is about 2,000 feet long and averages about 1,400 feet in width from the lake to the downstream toe. Maximum height of the blockage from the crest to the downstream toe is 190 feet, and from the crest to the lake 95 feet; vertical distance from the crest to the lake averages 60 feet. The altitude of the crest of the blockage ranges from 2,670 feet on the western side to 2,590 feet on the eastern side. Slopes average 28 percent from the crest of the blockage to the lake and range from 0.10 to 0.41 from the crest toward the Toutle River. The steepest slopes are on the western one-half of the blockage.

The thickness of the blockage was estimated by comparing pre-eruption topography of the blockage area (fig. 2; a 1:4,800 topographic map prepared by the Weyerhaeuser Company in 1950) and a post-eruption, 1:4,800 topographic map (fig. 3) prepared in 1981 under contract with the U.S. Geological Survey. A comparison of stream and ridge locations on the two maps indicates a problem with horizontal control for at least one of the maps and suggests that the blockage thickness (shown in figure 4) for any point could be in error by an amount greater than the 10-foot contour interval, perhaps as much as 100 feet in areas of steep relief.

Some instances of mass movement have occurred on the blockage, but to date they are all relatively small compared to the volume of the blockage. Twenty-one slope-failure scarps were mapped on the blockage using aerial photographs taken in the summer of 1982 (figs. 5 and 6). Additional features mapped on figure 6 include associated earthflow and debris-flow deposits, areas of standing water, fluvial surfaces (areas of running water or fluvial deposits), disturbed areas (roadways and other areas affected by construction of the spillway in fall 1981), and remnants of the original surface of the debris avalanche, relatively unaffected by human activities, water, or secondary mass movements. Using the classification of Varnes (1978), the slope failures include debris slumps, slides along a concave-upward rupture surface, and debris slides, where movement of material occurs along relatively planar detachment surfaces. The rims of the larger scarps are often formed by multiple smaller crescent-shaped scarps, as shown in figure 7, and therefore individual scarps mapped on figures 5 and 6 do not always represent a single mass movement. There is no evidence, from either the sequential aerial photographs or field observations, of continued retrogressive failure.

To better understand the processes that might contribute to weakening of the blockage, the approximate dates of appearance of slope-failure scarps were determined from aerial photographs taken at selected times between May 18, 1980, and March 6, 1982 (fig. 5). The first three failures occurred in locally steep areas of the blockage between May 18, 1980, and November 12, 1980. Fourteen more failures occurred from November 12, 1980, to March 1, 1981. Four failures occurred from March 1, 1981, to March 6, 1982. None of the failures encompassed large areas of the blockage. Failures from May 18, 1980, to March 1, 1981, are believed to result mainly from a combination of locally oversteep relief and surface saturation from precipitation during the first period of winter rains that followed the emplacement of the avalanche. The nearby Elk Lake earthquake that occurred on February 14, 1981, may have contributed to some of the failures, but this cannot be documented. The final four scarps plotted are located along the bank of Castle Creek, suggesting that the stream may have contributed to the instability by undercutting of its banks. If Castle Creek migrates toward the blockage, it could potentially change blockage geometry by erosion to the point that the blockage becomes unstable. This possibility is considered to be remote, but the morphology of the channel is being monitored frequently by aerial photographs and by repeated cross-sectional surveys.

In general, mass movements that have occurred on the blockage to date have occurred in areas where the topographic gradient was high, and by smoothing the relief of the blockage they may have served to increase overall blockage stability. There are no apparent surface manifestations of deep-seated instability.

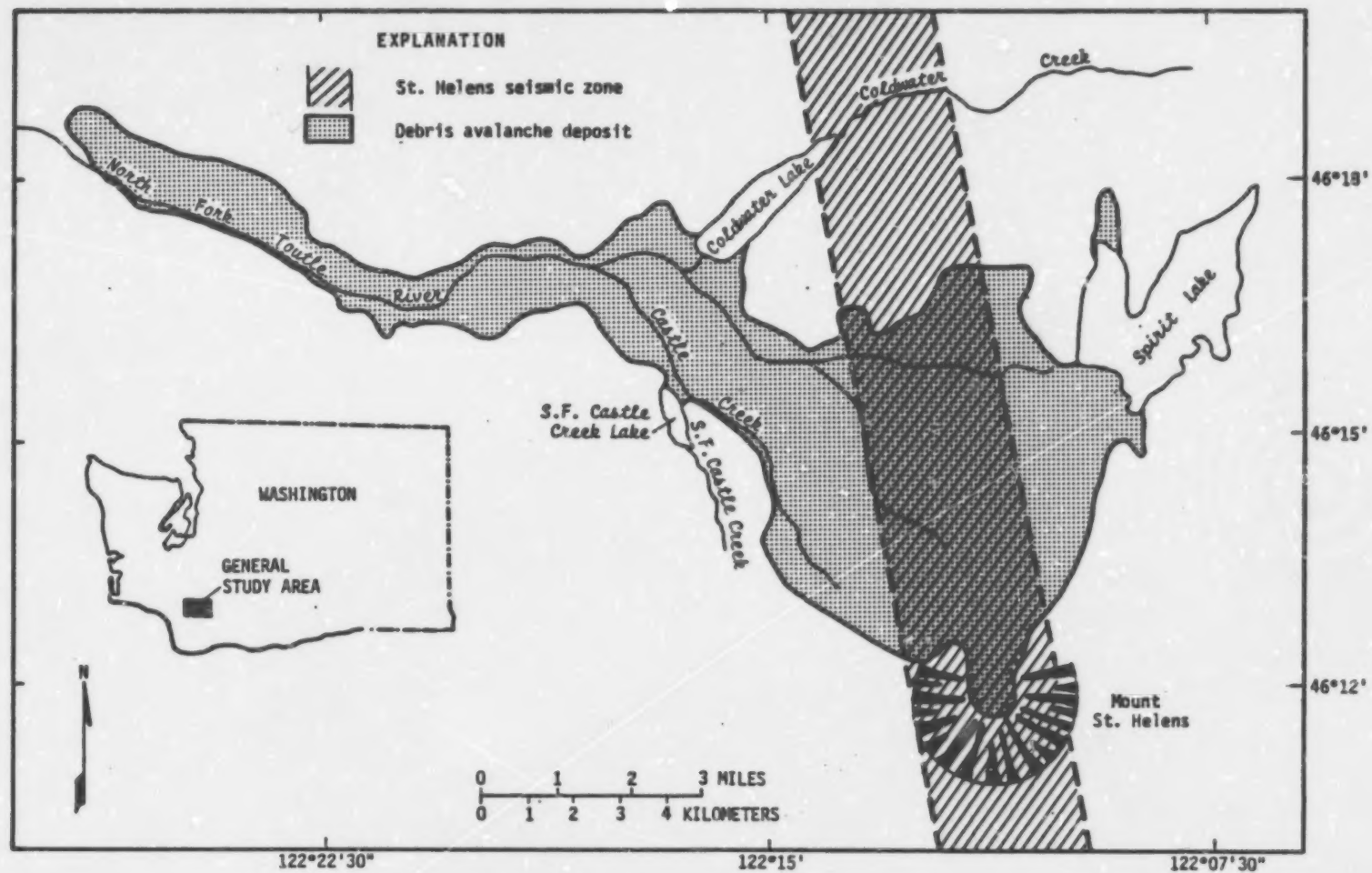


FIGURE 1.--Location of the study area and the Mount St. Helens seismic zone.

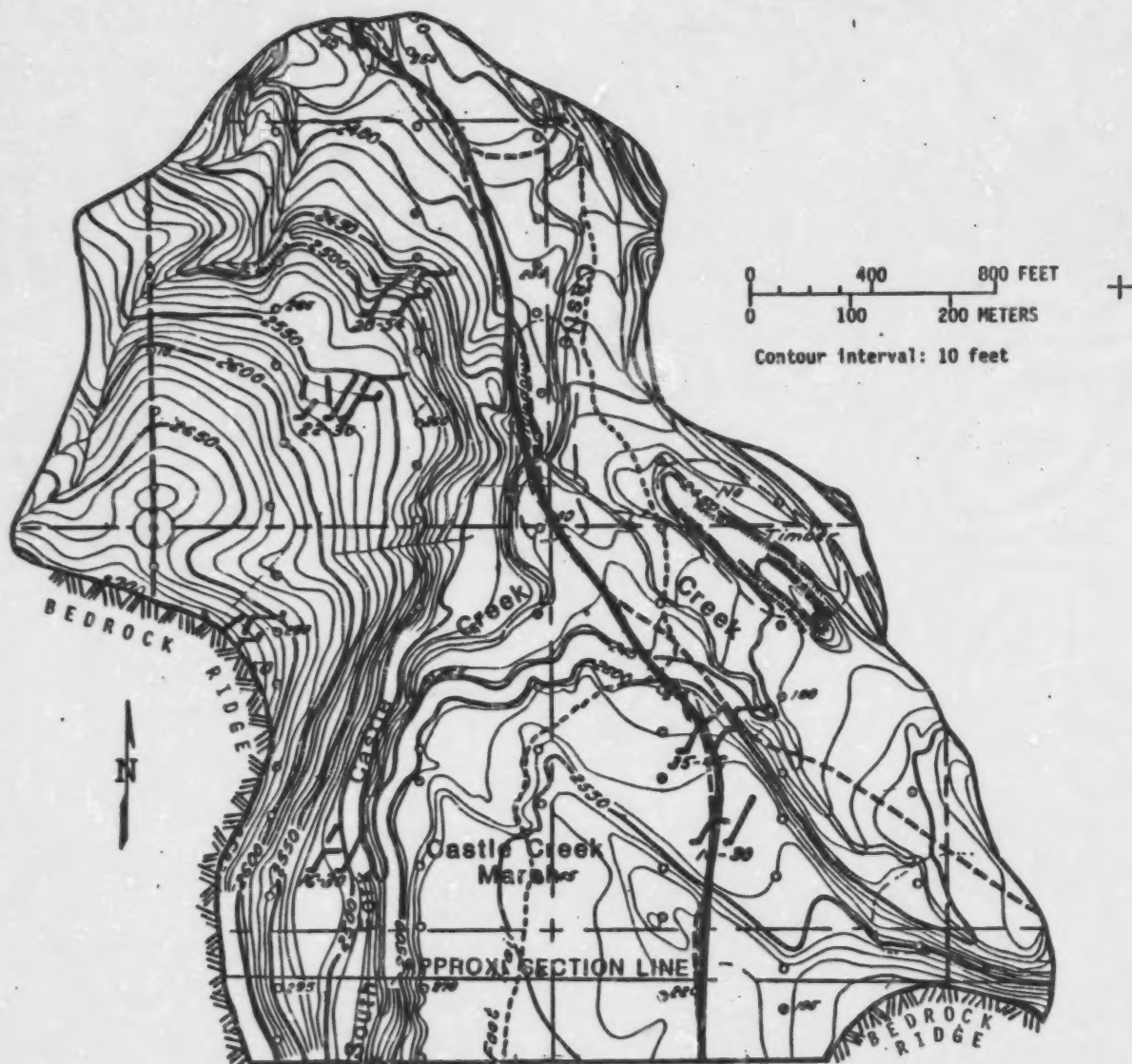


FIGURE 2.--Pre-eruption topography of the study area, prepared by the Weyerhaeuser Company in 1950.

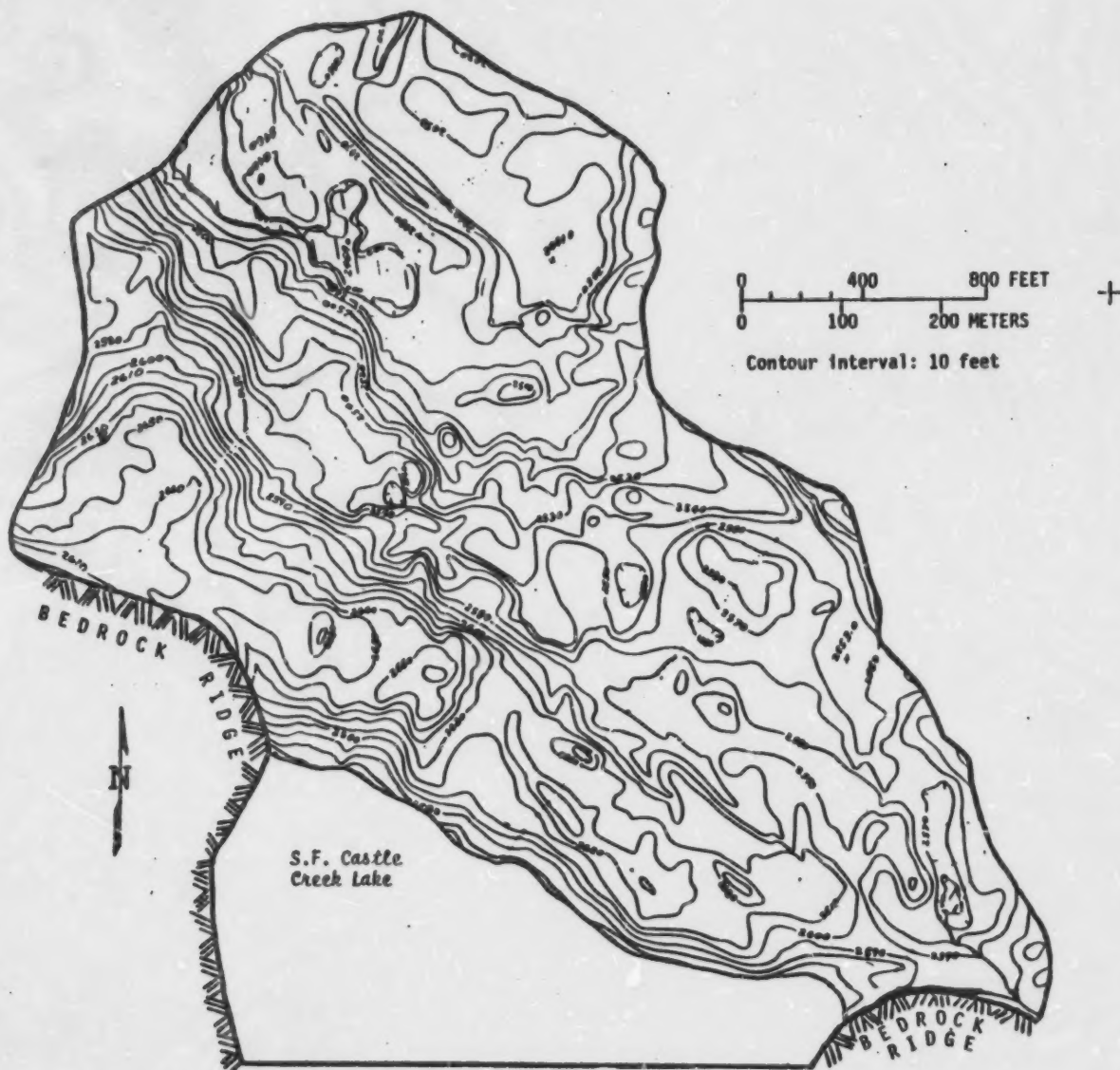


FIGURE 3.--Post-eruption topography of the South Fork Castle Creek blockage.

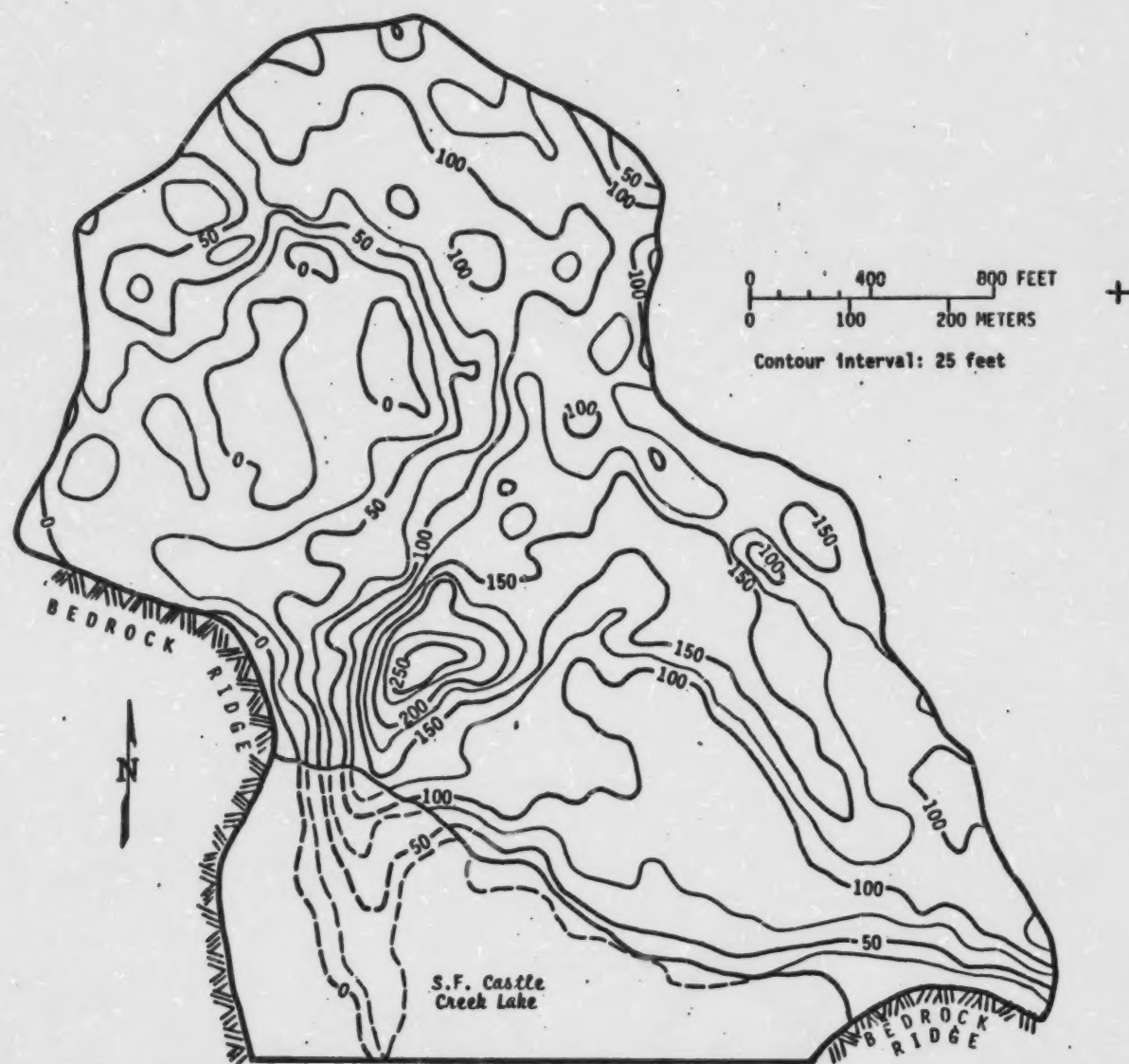


FIGURE 4.--Thickness of the South Fork Castle Creek blockage.

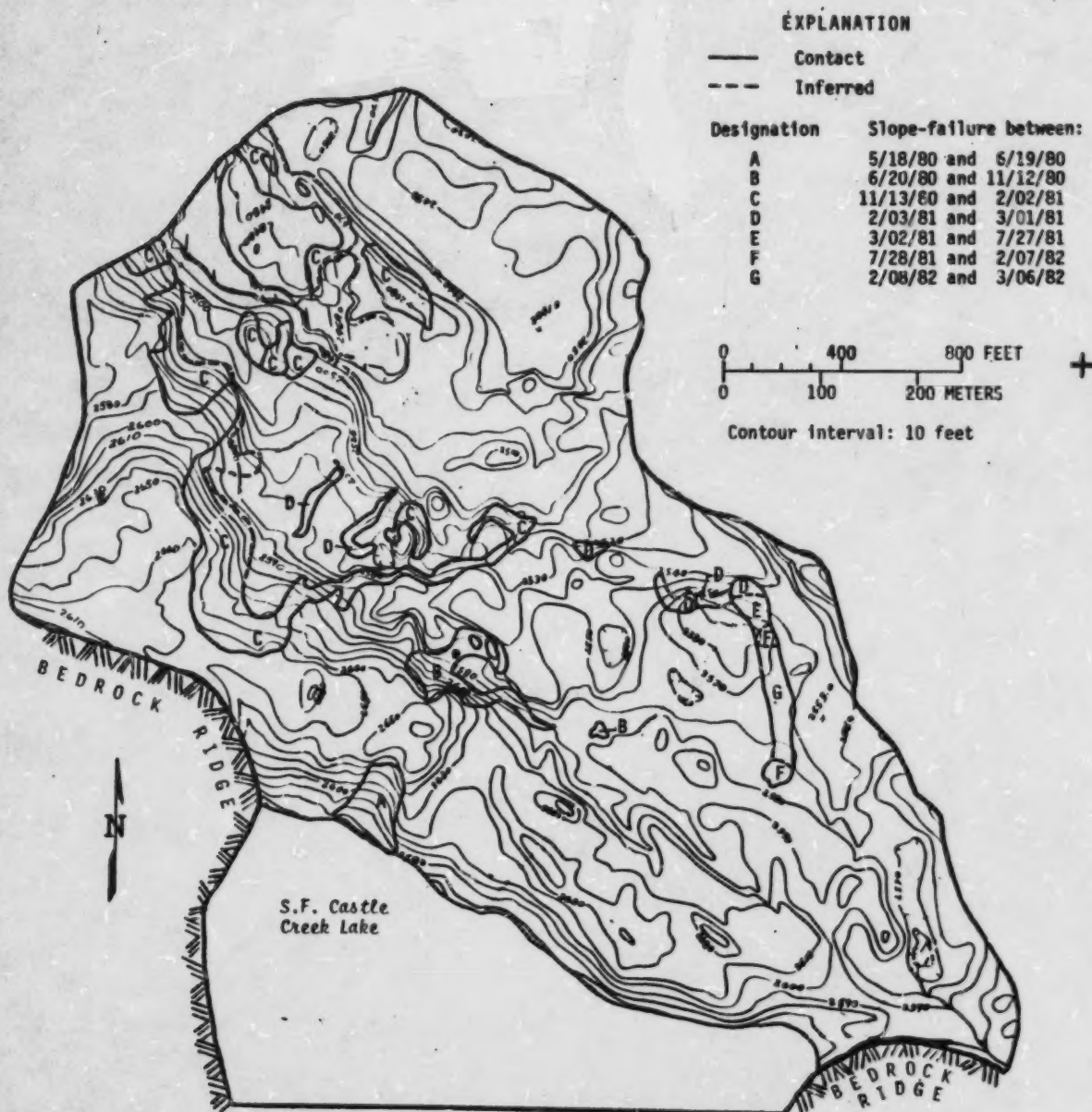


FIGURE 5.--Chronological appearance of slope-failure scarps on the South Fork Castle Creek blockage, as determined from aerial photography.

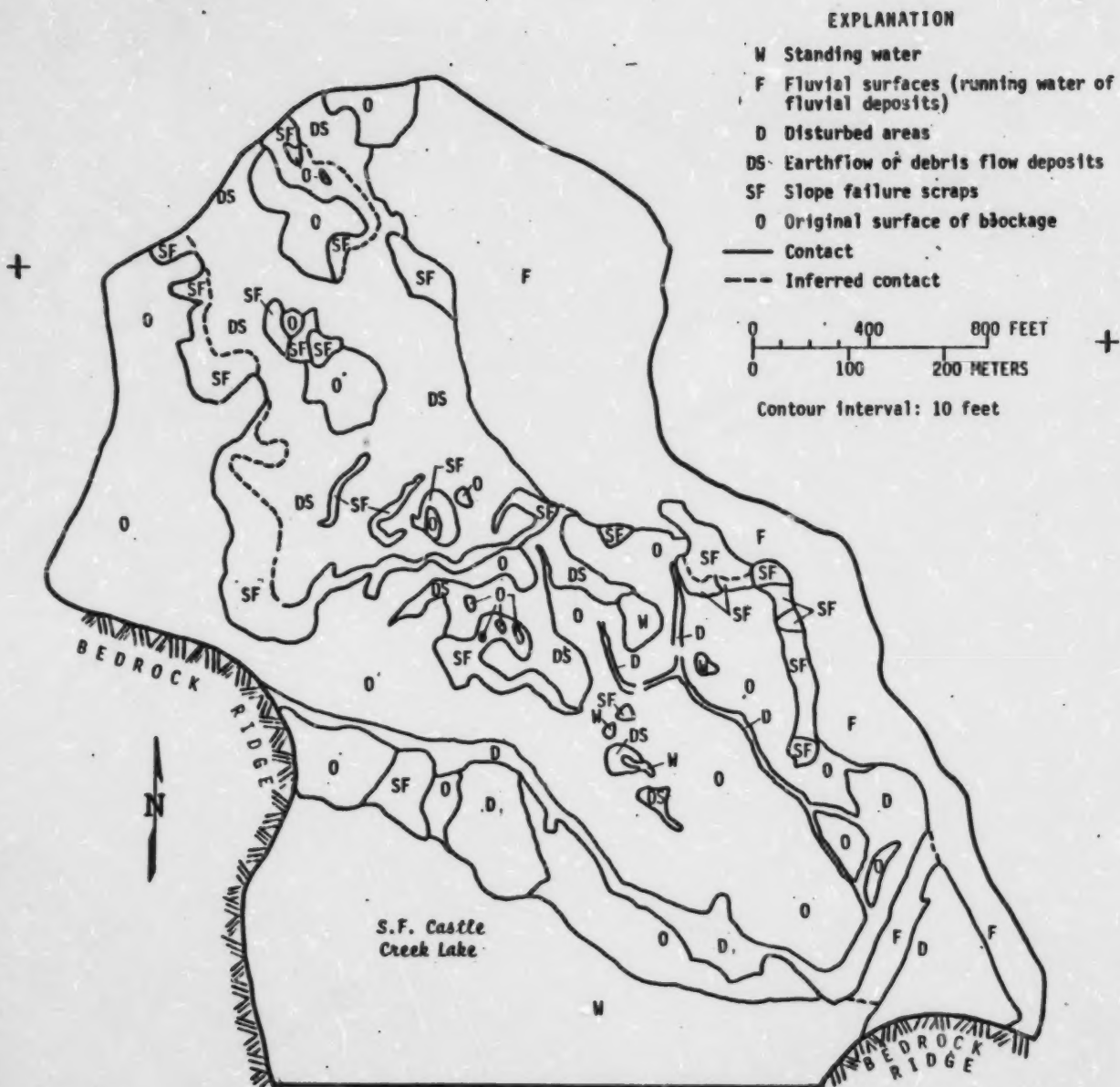


FIGURE 6.--Geomorphic features mapped at South Fork Castle Creek blockage on September 22, 1982.

LEFT

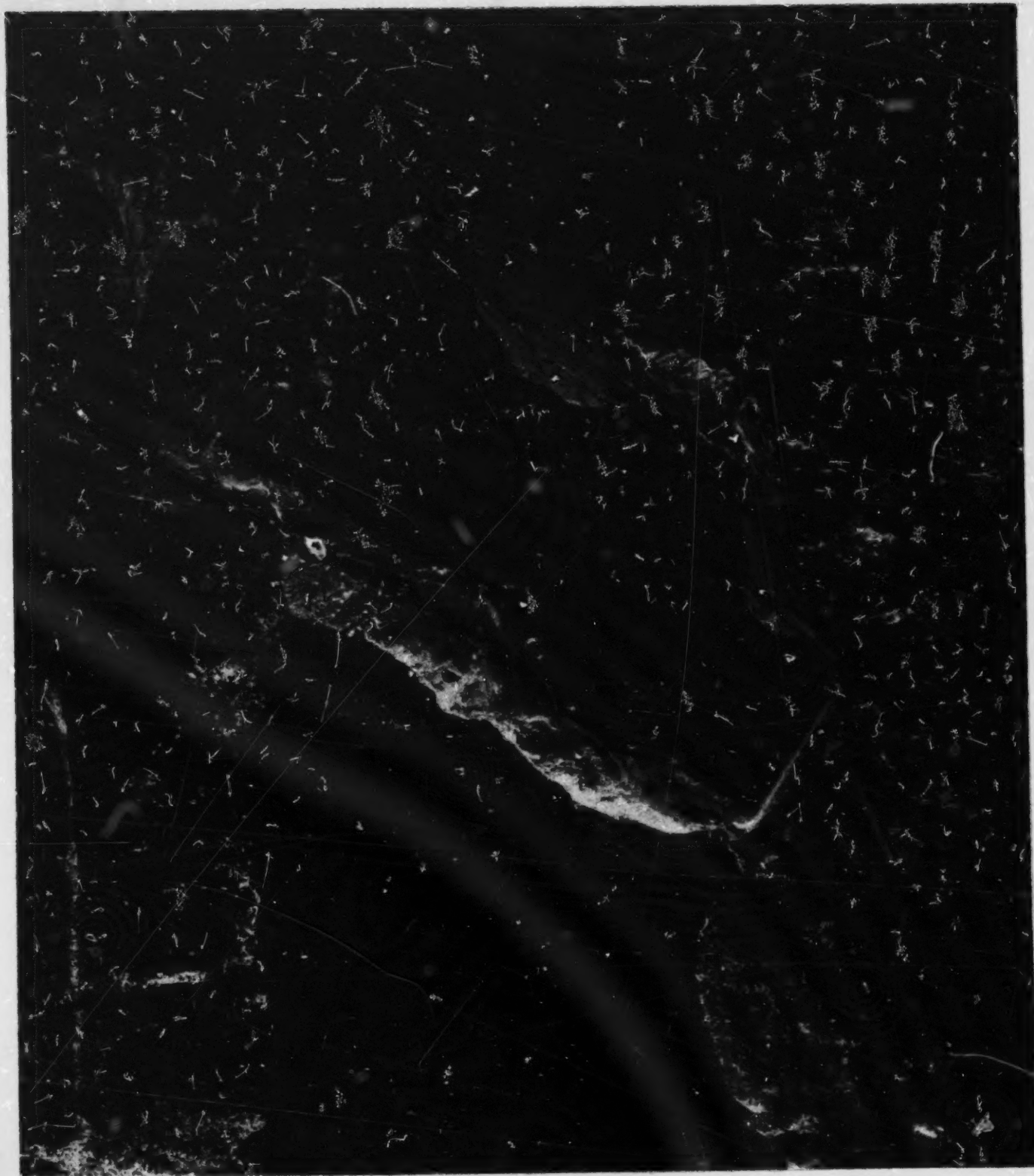


FIGURE 7.--Stereopair of aerial photographs taken of South Fork Castle Creek blockage on September 22, 1982, showing slope-failure detachment scarp formed of multiple crescents.

LIGHT

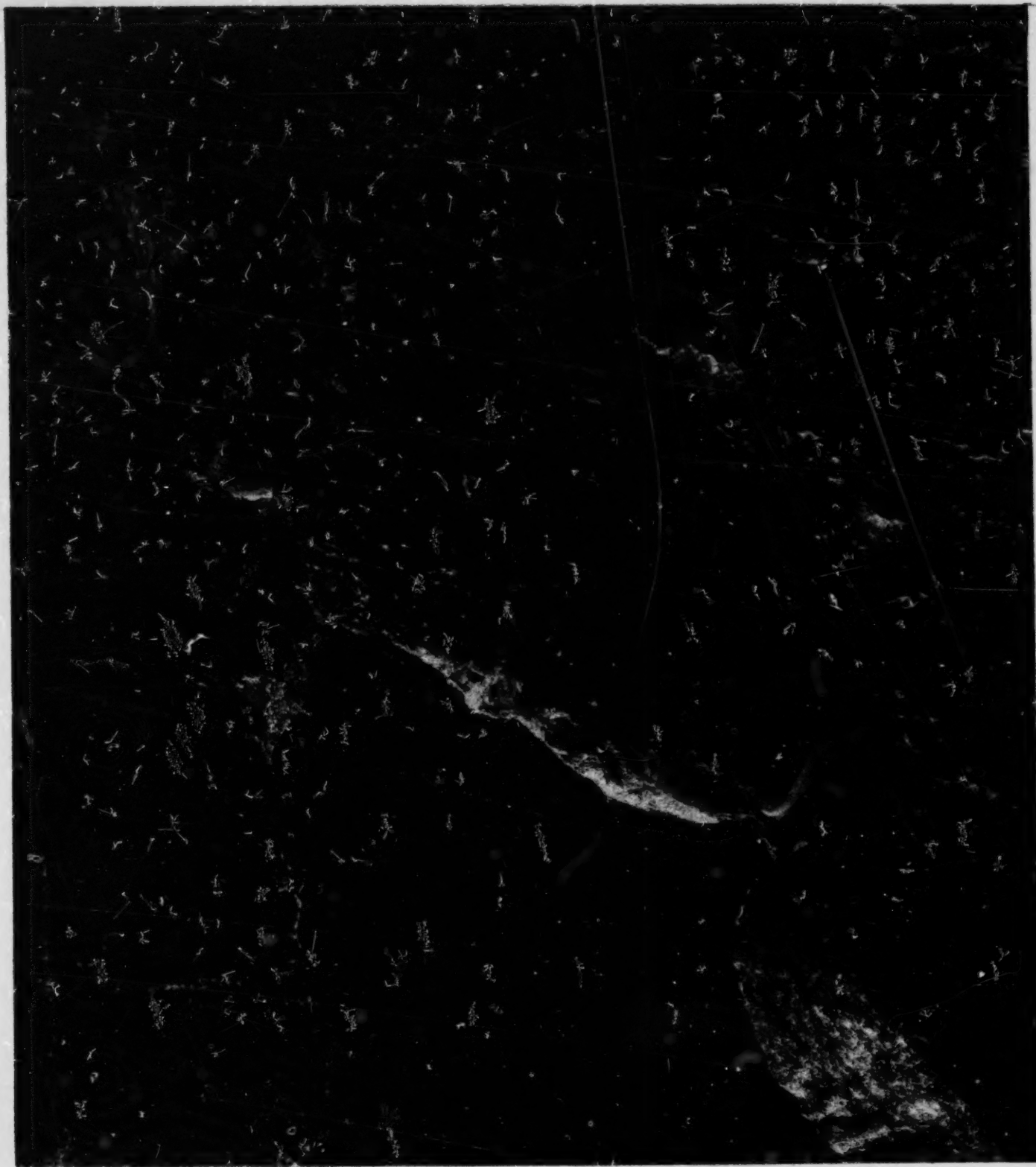


FIGURE 7.--continued.

GEOLOGIC SETTING

Pre-Eruption Geology

Castle Creek was contained within a 130-foot-deep channel cut into a broad northwestward-sloping fill of unconsolidated volcanoclastic debris from Mount St. Helens (fig. 2). This fill, of unknown thickness, is composed primarily of pyroclastic flows and lahars older than 2,500 years. However, exposures along the canyon revealed unconsolidated deposits younger than 180 years and an augite-hypersthene andesite lava flow 2,200-2,500 years old (C.A. Hopson, written commun., 1983). At the northern edge of the fill, a similar channel contained the North Fork Toutle River.

South Fork Castle Creek also flowed in a 130-foot-deep channel (fig. 2) cut into southwest-sloping unconsolidated volcanoclastic deposits from Mount St. Helens older than 2,500 years (C. A. Hopson, written commun., 1983). The thickness of these deposits is also unknown. One mile south of the conjunction of Castle Creek and South Fork Castle Creek was a swampy, flat, alluvium-filled area called Castle Creek Marsh (fig. 2). The southwesterly slope of the volcanoclastic material indicates that thick pyroclastic flows or lahars from Mount St. Helens flowed up South Fork Castle Creek and probably blocked it in prehistoric time, forming a lake at the site of Castle Creek Marsh. When the ancient lake filled, the water from the lake probably overtopped the prehistoric blockage and drained suddenly, in a manner similar to that of some of the smaller lakes on the 1980 debris-avalanche deposit (Jennings and others, 1981). If this scenario is correct, the channel of the pre-May 18, 1980, South Fork Castle Creek was eroded at the time of the ancient lake breakout.

The valleys containing Castle Creek and South Fork Castle Creek are both bounded by bedrock ridges composed of the Eocene or late Miocene Ohanapecosh Formation. The Ohanapecosh in this area consists of andesitic and dacitic volcanic rocks, both lava flows and breccias, and associated volcanoclastic sedimentary rocks. The Ohanapecosh has undergone widespread low-temperature, low-pressure zeolite facies alteration (C. A. Hopson, written commun., 1983).

Post-Eruption Geology

The South Fork Castle Creek blockage is composed almost entirely of the deposit of the debris avalanche of May 18, 1980 (figs. 8 & 9), mapped and described by Voight and others (1981). The debris-avalanche deposit is overlain by blast pyroclastic-flow deposits (Lipman, 1981), generally less than 1 foot thick but more than 15 feet thick in lower areas of the blockage. Ash falling from the air during the eruptions of May 18, May 25, and August 7, 1980, is less than 1 inch thick at the blockage (Sarna-Wojcicki and others, 1981).

Debris-Avalanche Deposit

Voight and others (1981) indicated that the South Fork Castle Creek blockage is composed of lateral deposits (levee material) of the North Toutle unit of the debris-avalanche deposit. The units mapped by Voight and others are identified primarily on the basis of unmodified morphologic characteristics. Because the blockage is composed of levee material, the slopes of the ridges and hummocks that make up the blockage are steeper than those of the bulk of the debris-avalanche deposit. However, the lithologic composition of the levee material is distinctly different from the bulk of the avalanche deposit.

The blockage consists of two major lithologic units that are informally referred to in this report as the ancestral dacite unit and the modern dacite, andesite, and basalt unit. In addition, a small area of blast pyroclastic-flow deposits that in places overlie ancestral dacite was mapped where the blast deposits are more than 5 feet thick (fig. 8). These units are described on the basis of field characteristics; detailed petrographic results are not included.

Modern dacite, andesite, and basalt unit

The modern dacite, andesite, and basalt unit (dmu on fig. 8) is an unsorted, mostly unstratified mixture of material ranging from silt-clay size to boulders up to 5 feet across. The rock types in the unit are predominantly dacite, andesite, and basalt from the modern (less than 2,500 years old) cone of Mount St. Helens, as mapped by C. A. Hopson (written commun., 1983). (The distinction between the lavas of the modern cone and an underlying "old Mount St. Helens series" was noted by Verhoogen (1937). Hopson (written commun., 1983) referred to "modern" and "ancestral" lavas, and his terminology is adopted for this report.)

Minor amounts of ancestral dacite, dacitic pumice, and organic debris from the old mountain are also found in the modern dacite, andesite, and basalt unit, but the proportions are difficult to estimate because of the lack of good exposures. Examination of surficial float and selected outcrops cleared of slopewash suggests that dacite, andesite, and basalt from the modern cone of Mount St. Helens make up more than 75 percent of the unit.

The modern dacite must have come from the Goat Rocks or the Summit domes or from their volcanoclastic debris. These were the only dacite exposures on the pre-May 18, 1980, Mount St. Helens edifice and were the only two domes less than 2,500 years old that were incorporated in the debris avalanche (Voight and others, 1981). The Goat Rocks and Summit domes were composed of augite-hornblende-hypersthene dacite that is grey when fresh and various shades of red or pink when hydrothermally altered. The dacite is nearly aphyric in hand specimen, but close examination reveals microphenocrysts of hornblende, pyroxene, and plagioclase, generally less than 0.1 inch long. Xenoliths of varying composition are common in these and other domes of Mount St. Helens (Hopson, oral commun., 1980).

The modern andesite and basalt rocks within the debris-avalanche deposit are derived from various lava flows on the pre-1980 edifice of Mount St. Helens (Verhoogen, 1937, and Hopson, written commun., 1983), indistinguishable from each other in hand specimen. The rocks are generally black or dark grey, but are locally various shades of green or red when hydrothermally altered. The andesite is generally plagioclase phyric with varying amounts of hypersthene and augite. Olivine is rare and usually occurs as phenocrysts less than 0.05 inch across. The basalt is either aphyric or olivine-phyric and is much less abundant than the andesite. The andesite and basalt range from non-vesicular to scoriaceous.

Ancestral dacite unit

The ancestral dacite unit (da on fig. 8) is an unsorted, unstratified mixture of material ranging from silt-clay size to clasts many feet in diameter. It is much more homogeneous than the modern dacite, andesite, and basalt unit, and consists almost entirely of the "ancestral dacite" lithology, often hydrothermally altered. However, lenses of andesitic breccia, generally less than 1 square foot in dimension, are observed locally. These probably represent brecciated andesite dikes, created from dikes similar to the undeformed dikes observed in the present (1983) crater of Mount St. Helens. Brecciated dikes may also be blended into the ancestral dacite; of 100 pebbles ranging from 1 to 4 inches in diameter that were examined at one exposure, 88 percent are ancestral dacite and 12 percent are other lithologies, primarily andesite.

The ancestral dacite originates from the complex of dacitic domes and associated breccias older than 2,500 years that make up the core of Mount St. Helens. These rocks are present in the light-colored exposures in the 1980 crater below 7,500 feet, and form a few domes that are exposed around the flanks of the mountain. The ancestral dacite lithology is readily identified in the field. It is a hornblende-hypersthene dacite, grey when fresh and various shades of red, pink, and green when hydrothermally altered. It contains prominent phenocrysts of hornblende and plagioclase greater than 0.1 inch long, as well as less prominent hypersthene phenocrysts. Xenoliths of varying composition are present locally.

Blast Pyroclastic-Flow Deposits

The blast pyroclastic-flow deposits (bp on fig. 8) are the hot, highly fragmented deposits of the directed blast of May 18, 1980. They were mapped only in the northwest corner of the study area where they are more than 5 feet thick and overlie ancestral dacite.

Where exposed, they are generally a poorly sorted, unstratified mixture of angular material ranging in size from silt-clay to fragments several inches in diameter. They are identified by an undulating, wavy upper surface, and by olive-grey exposures that contain a blended mix of all pre-1980 Mount St. Helens rock types. They contain a characteristic prismatically jointed, semi-vesicular, steel-blue-grey hypersthene-hornblende dacite that is referred to as "blast dacite" and is thought to be juvenile material, representing fragments of the pre-May 18, 1980, cryptodome (Hoblitt and others, 1981).

On the higher areas of the blockage, the blast pyroclastic-flow deposits are generally finer grained and generally do not contain clasts larger than half an inch in diameter. The unit here has characteristics similar to layers A2 and A3 of Waitt (1981) and the pyroclastic surge and accretionary lapilli units of Hoblitt and others (1981).

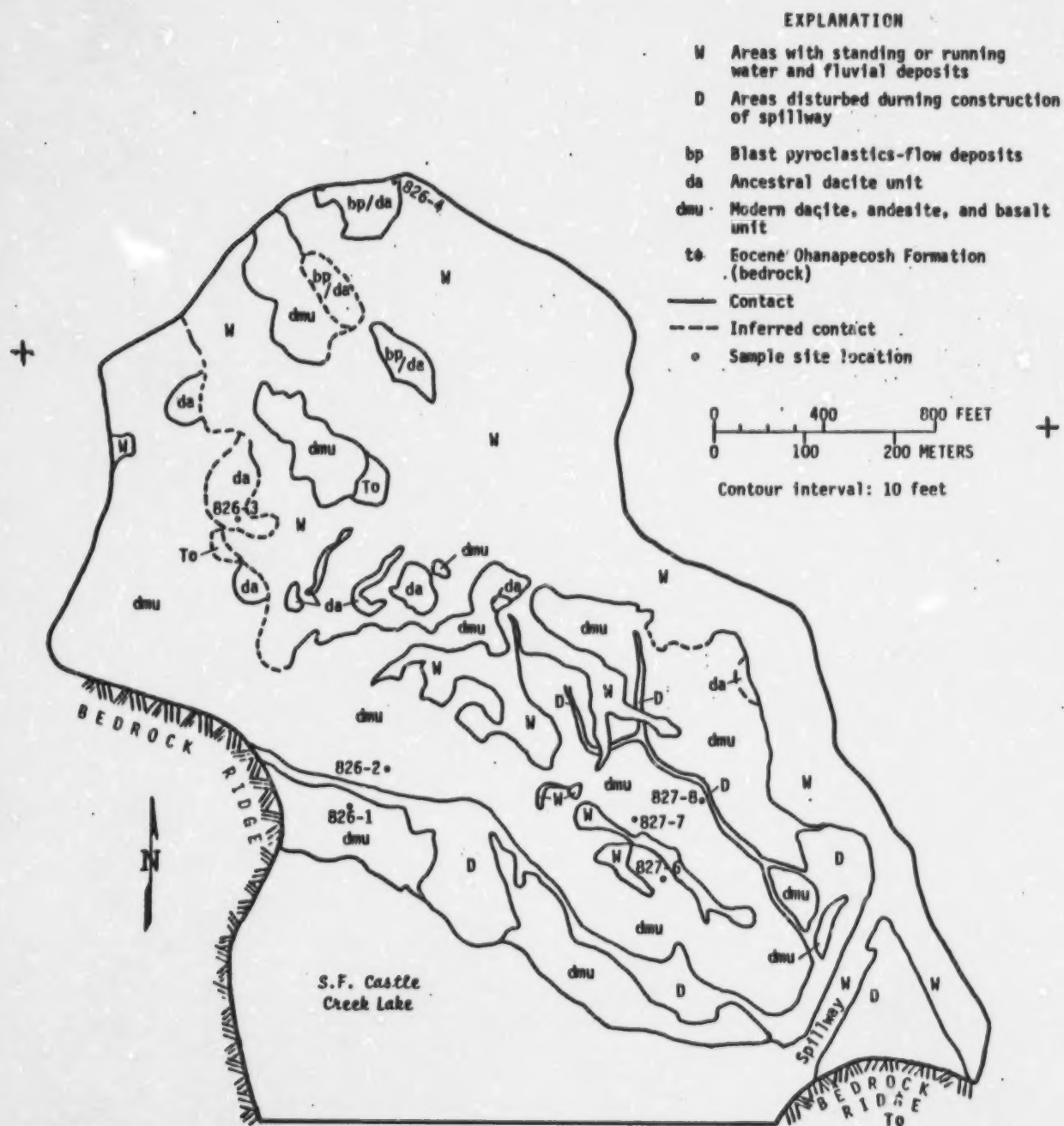


FIGURE 8.--Geology of the study area.

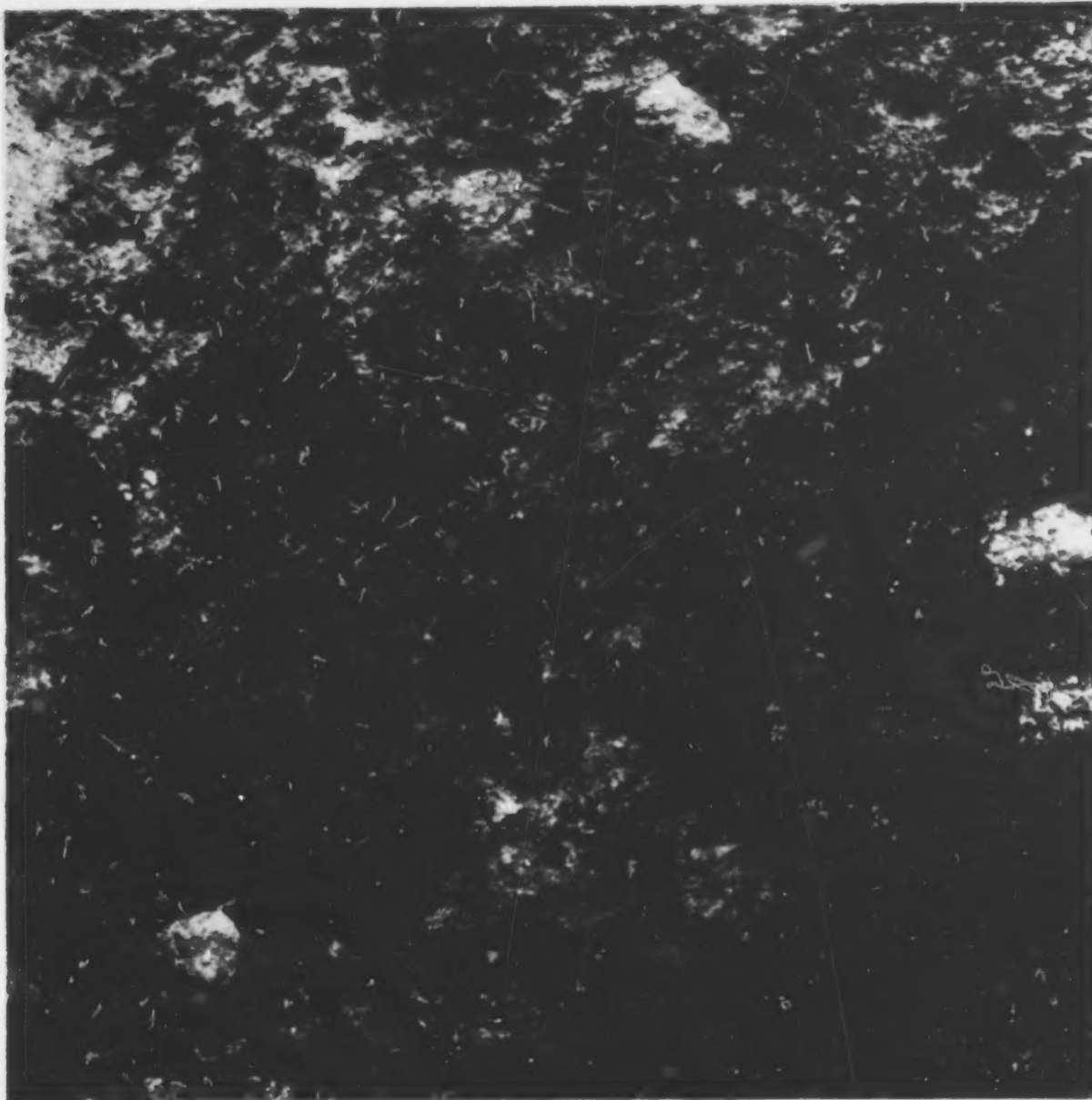


FIGURE 9.--Typical exposure of blockage material.

PHYSICAL PROPERTIES OF BLOCKAGE MATERIAL

Texture

Samples weighing from 4 to 11 pounds were collected in the blockage material at five sites in the modern dacite, andesite, and basalt unit (which composes most of the blockage) and at one site each in the ancestral dacite unit and blast pyroclastic-flow deposits to determine particle-size distribution. Only particle sizes less than 64 mm (see conversion table, p. vi, for conversion factors) were considered in the analysis, although blocks up to meters in diameter are present locally. All the units are poorly sorted. Silt and clay content for the samples from the modern dacite, andesite, and basalt unit ranged from 7.0 percent to 12.8 percent, sand content from 36.8 to 47.0 percent, and gravel content from 43.6 to 56.2 percent. Corresponding values for the single sample from the ancestral dacite unit were 9.2, 49.0, and 41.8 percent, and for the blast pyroclastic-flow deposit 16.0, 50.9, and 33.1 percent. Median diameters for the modern dacite, andesite, and basalt unit ranged from 0.7 to 3.5 mm; for the ancestral dacite unit, sample median diameter was 1.1 mm and for blast pyroclastic-flow deposits, 0.5 mm. Uniformity coefficients (table 1) ranged from 25 to 91; those values are lower than the average of 104 reported for the avalanche as a whole by Voight and others (1981).

Particle-size data alone provide an incomplete picture of the texture of the modern dacite, andesite, and basalt unit. When vertical exposures of at least 10 square feet are cleared of loose material, many lithologically distinct blocks of breccia from the old mountain can be seen in the unit in various degrees of disaggregation. A typical exposure is shown in figure 6. Although the material properties are slightly different from block to block, the range is probably reasonably represented by the sampling.

Unit Weight and Relative Density

Physical properties of particle sizes less than 4.75 mm were determined for five samples of modern dacite, andesite, and basalt unit, one sample of ancestral dacite unit, and one sample of blast pyroclastic flow deposit on the blockage and at other sites on the debris-avalanche deposits (table 2). Physical properties of samples from five selected sites on the debris avalanche outside of the blockage are also shown for comparison.

True specific gravities of the modern dacite, andesite, and basalt unit solids particles from the sieved sample fraction less than 4.75 mm ranged from 2.57 to 2.70 (table 2). The samples of the ancestral dacite and blast pyroclastic flow units had specific gravities of 2.68 and 2.69.

Dry unit weight (γ_d), determined by the sand-cone method, gave values for the avalanche in the range of 90 to 120 lb/ft³ (table 2). This wide range and the low average value of 102 lb/ft³ possibly reflects late- and (or) post-depositional disturbances of portions of the blockage, because materials in sheared or slumped levee walls and boundary zones have been observed locally to be less dense than less disturbed debris elsewhere on the avalanche (Voight and others, 1981). However, operator error is suspected in several of these measurements. Three measurements considered reliable give a range of 106 to 120 lb/ft³, with an average of 114 lb/ft³ (Youd, Schuster, and Voight, written commun., 1983). One sample of the blast pyroclastic-flow deposit yielded a dry unit weight of 126 lb/ft³.

Water content w , the weight of water divided by the weight of dry solids and expressed as a percentage, ranged from 3.0 to 9.3 and averaged 6.9 percent. Because samples were obtained near the surface following a dry period in August 1982, these values are perhaps low when compared with representative material at depth.

Including unreliable samples, the calculated average wet unit weight (the product of $(1 + w)$ and dry unit weight) for the South Fork Castle Creek blockage at the time of sampling was 109 lb/ft³. The average value was 122 lb/ft³ for reliable measurements.

By comparison, wet-unit-weight measurements for four large-size samples (6 feet in diameter and several feet thick) from the debris-avalanche deposit near Spirit Lake averaged 120 lb/ft³ for an average water content of about 8.8 percent (three samples; T. J. Seeman, written commun., 1983). On the basis of these measurements, the average dry unit weight is 108 lb/ft³, a value somewhat less reliable than the wet weight because of assumptions made about water content. The average dry unit weight for 36 conventional sand cone measurements widely distributed over the avalanche is 119 lb/ft³ (H. X. Glicken, written commun., 1983). The more reliable data from the blockage, with an average dry unit weight of 114 lb/ft³, thus suggest that unit-weight values are similar to those for other sites on the debris-avalanche deposit.

Relative densities, D_r , (Terzaghi and Peck, 1967) were calculated by comparing field dry unit weights, γ_d , with laboratory-determined maximum and minimum unit weights, γ_{dmax} and γ_{dmin} , and are reported as percentage:

$$D_r = \left(\frac{\gamma_d - \gamma_{dmin}}{\gamma_{dmax} - \gamma_{dmin}} \right) \left(\frac{\gamma_{dmax}}{\gamma_d} \right) \cdot 100$$

Laboratory tests were performed on samples from the blockage using material 3 inches or less in diameter in 0.5-cubic-foot cylindrical molds. Maximum unit weights were determined using dry samples subjected to a 0.14-ton-per-square-foot surcharge on a vibratory table. Minimum unit weights were gained by gentle placement of debris into the mold, and the test was repeated until consistent results to within 1 percent were obtained.

For the samples from the South Fork Castle Creek blockage, relative density of the blast pyroclastic-flow deposit sample was 93 percent and of one sample from the debris-deposit avalanche, 55 percent. For the remaining samples from the debris-avalanche deposit, relative density was less than 0 (that is, dry unit weight is less than minimum unit weight) (table 2). The result, $D_r < 0$, is probably caused by erroneous field determinations of dry unit weight. Laboratory determinations of dry densities are considered to be accurate (table 2); in these tests, average values of minimum and maximum dry unit weight for five samples from the modern dacite, andesite, and basalt unit were 105.1 and 122.9 lbs/ft³, respectively. Using these as extreme values, the average field dry unit weight of 113.9 lbs/ft³ for these samples (based on three measurements that were considered reliable) corresponds to a relative density of 53 percent. The average of 25 determinations of relative density distributed over the entire avalanche is 48 percent, a comparable value. Although fragmentary, the data suggest that the degree of compaction of the deposit at South Fork Castle Creek is probably typical of all avalanche debris.

Strength

Laboratory-drained direct-shear tests were conducted at the North Pacific Division Material Laboratory, U.S. Army Corps of Engineers, Portland, Oreg., on representative splits of one sample from the blast pyroclastic-flow deposit and three samples from the modern dacite, andesite, and basalt unit (T. J. Seeman, written commun., 1983). The fraction of the samples less than 4.75 mm was compacted to approximately field density, as estimated by sand cone measurements in a 3-inch-square by 0.75-inch-thick shear box. A normal pressure of 3 tons/ft² was applied, and after a 24-hour soaking period, shearing was accomplished at a rate of 0.001 inch per minute to a displacement of 0.5 inch. The procedure was repeated on fresh sample splits for normal pressures of 5 and 10 tons/ft².

The samples from the debris-avalanche deposit show slight development of peak strength and mainly contractive volumetric changes, characteristic of loose specimens of particulate material and in keeping with the low field estimates of dry unit weight. Linear Coulomb regressions for individual samples give effective stress-friction angles (ϕ') of 35 to 38 degrees and cohesion intercepts (c') of from 0.10 to 0.25 ton/ft² (table 2). Forcing the Coulomb envelope through the origin gives apparent friction angles (ϕ^*) of 36 to 38.5 degrees fitted through data points in the 3- to 5-tons-per-square-foot normal pressure range (table 2).

Combined data for samples from the modern dacite, andesite, and basalt unit give, by least squares analysis, an average intercept of 0.16 ton/ft² and peak ϕ' of 36.4 degrees ($r^2 = 0.996$; figure 10a). Also for combined data, peak ϕ^* is 37.1 degrees ($r^2 = 0.999$) and ultimate ϕ^* is 34.9 degrees ($r^2 = 0.999$; figure 10b). These peak strength estimates for these samples are conservative, because the strength tests were carried out at a degree of compaction believed to be small compared to the more reliable field estimates. A comparison sample, DXS-3, taken adjacent to the blockage in debris composed mainly of modern dacite, gave comparable values (table 2).

The sample from the blast pyroclastic-flow deposit, with $D_r = 93$, was stronger than the sample from the modern unit debris-avalanche sample, with $\phi' = 41.5$ degrees and $c' = 0.50$ ton/ft², and peak $\phi^* = 44$ degrees. Combined results for five samples from the blast pyroclastic-flow deposit at various sites between Castle Creek and Spirit Lake (average $D_r = 61$) indicate peak $\phi' = 33.64$ degrees and $c' = 1.42$ tons/ft² ($r^2 = 0.721$); peak $\phi^* = 39$ degrees ($r^2 = 0.932$), and ultimate $\phi^* = 33.6$ degrees ($r^2 = 0.966$).

Strength determinations were not made for the ancestral dacite unit of the debris-avalanche deposit, but the combined results for four samples from the ancestral dacite unit from other sites on the avalanche (table 2) are: peak $\phi' = 31.6$ degrees and $c' = 1.80$ tons/ft² ($r^2 = 0.775$); peak $\phi^* = 39.4$ degrees ($r^2 = 0.942$), and ultimate $\phi^* = 33.5$ degrees ($r^2 = 0.975$) (figs. 11a and b). These results imply strength values somewhat lower than those given by Voight and others (1981) for samples distributed over the avalanche. They reported peak friction angles of about 38 to 44 degrees for the same

particle-size range for nine avalanche samples. The analysis of the latter samples assumed zero cohesion, and thus their friction angles are comparable to values of ϕ^* determined during this study. Similarly, T. L. Youd and others (written commun., 1981) reported a peak angle of 42.5 degrees for a single sample of debris-avalanche deposit. Both papers described reduction of friction angle (ultimate strength) as a function of displacement, and this concept is sustained by our results.

The cohesion values reported here are influenced by several factors. In some instances, sample heterogeneity has resulted in scattered data points on a Coulomb plot; linear regression results in a cohesion intercept that is more a reflection of data scatter than of finite strength at low normal pressure. In other instances, the data imply an intercept if a linear regression is assumed. Some workers might prefer to assume $c' = 0$ and restrict strength envelopes to linear, or nonlinear, regression lines passing through the origin (Voight and others, 1981). The cohesions are generally considered "apparent" values, mainly reflecting incomplete saturation of test specimens during shear. Although breakage of angular grains might conceivably have occurred in some tests (particularly in some samples from the ancestral dacite unit of the debris-avalanche deposit), the reported cohesions do not represent reproducible strength components that can be relied upon in the analysis of slope stability.

**TABLE 1.--Initiation dates of minor mass movements at South Fork
Castle Creek blockage and number of mass movements in
each initiation period**

<u>Designation</u>	<u>Date of initiation</u>
A	May 18, 1980 - June 19, 1980,
B	June 20, 1980 - Nov 12, 1980
C	Nov. 13, 1980 - Feb 2, 1981
D	Feb. 3, 1981 - March 1, 1981
E	Mar. 2, 1981 - July 27, 1981
F	July 28, 1981 - Feb 7, 1982
G	Feb. 8, 1982 - March 6, 1982

TABLE 2.--South-Fork Castle particle-size distribution

Sample number	Geologic unit	Particle-Size Classification			Median diameter (mm)	Gradation	
		Gravel (percent)	Sand (percent)	Silt-clay (percent)		Uniformity coefficient ¹	Sorting coefficient ²
82-826-1	Modern dacite and lavas	43.6	47.0	9.4	0.7	42	5
82-826-2	Modern dacite and lavas	54.9	37.3	7.8	1.3	42	6
82-827-8	Modern dacite and lavas	56.2	36.8	7.0	3.5	91	8
82-827-6	Modern dacite and lavas	48.9	40.7	10.4	1.7	74	8
82-827-7	Modern dacite and lavas	44.8	42.4	12.8	1.2	66	8
82-826-3	Ancestral dacite	41.8	49.0	9.2	1.1	37	6
82-826-4	Blast pyroclastic-flow deposit	33.1	50.9	16.0	0.5	25	6

¹Uniformity coefficient (Hazen's) - ratio of the diameter at the 60 percent finer point and that at the 10 percent finer point on a gradation curve.

²Sorting coefficient of Inman (1952).

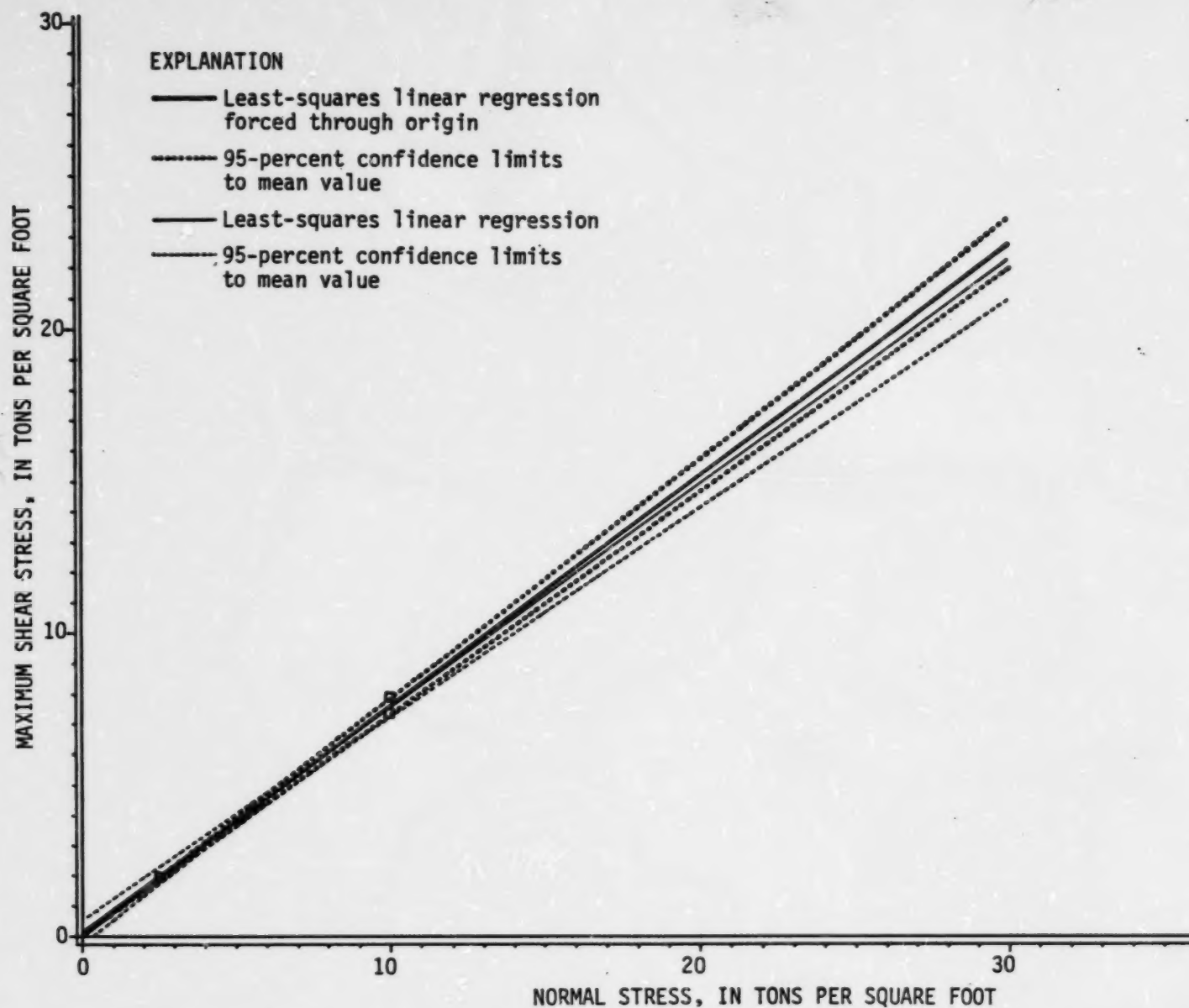


FIGURE 10a.--Results of direct shear-strength tests on the modern dacite, andesite, and basalt unit of the South Fork Castle Creek blockage: peak strength.

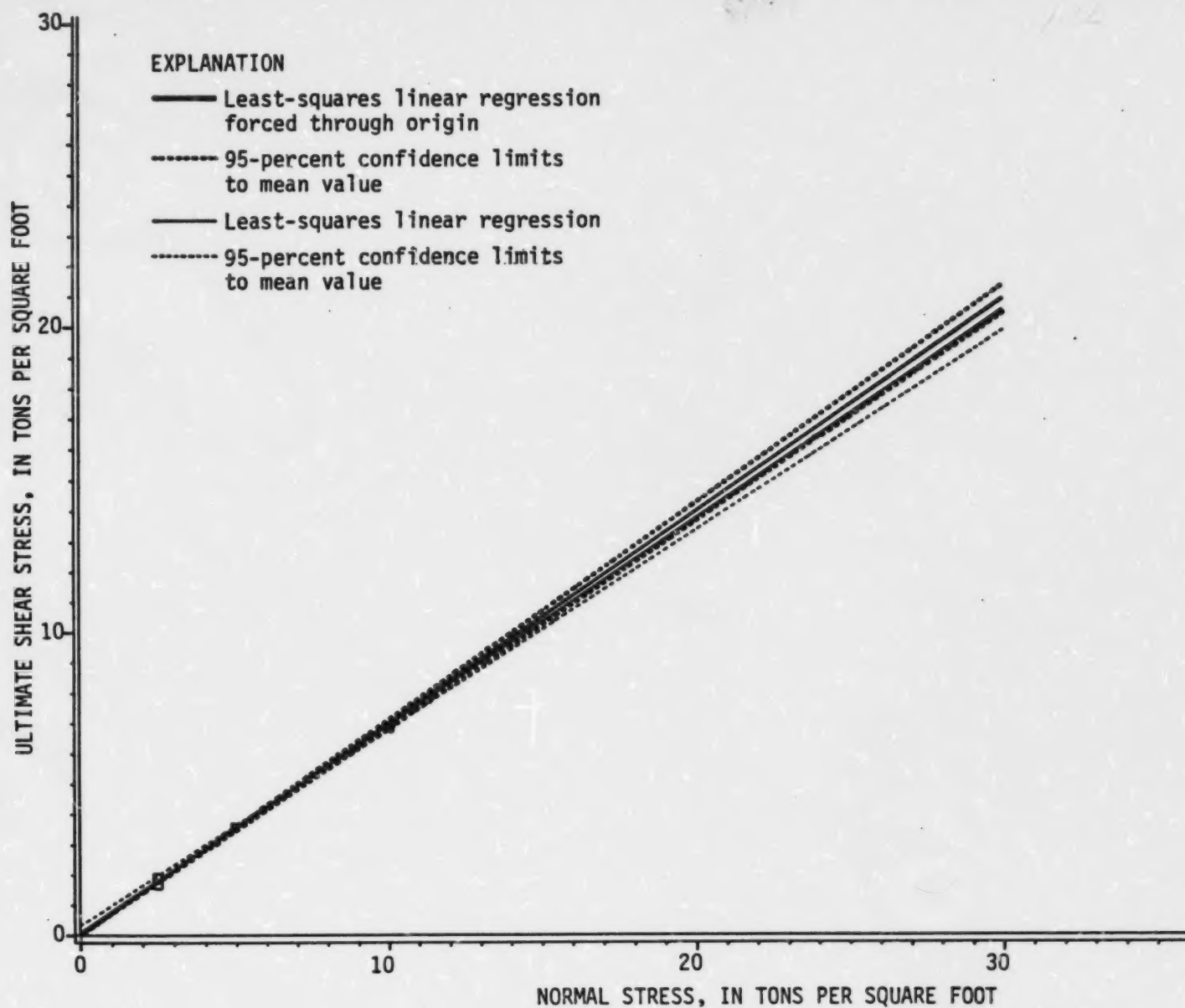


FIGURE 10b.--Results of direct shear-strength tests on the modern dacite, andesite, and basalt unit of the South Fork Castle Creek blockage: ultimate strength.

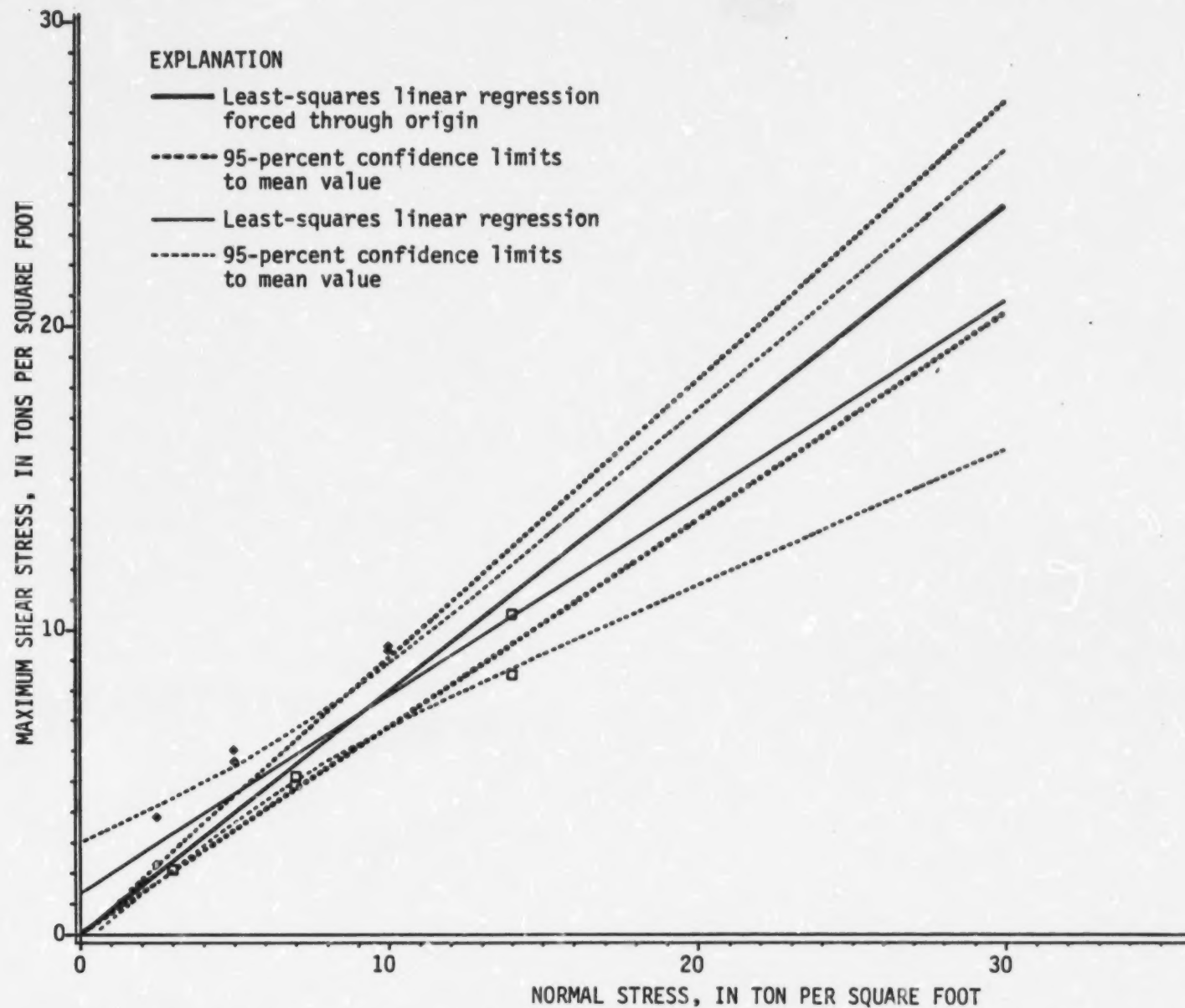


FIGURE 11a.--Results of direct shear-strength tests on the ancestral dacite unit of the avalanche debris from various sites: peak strength.

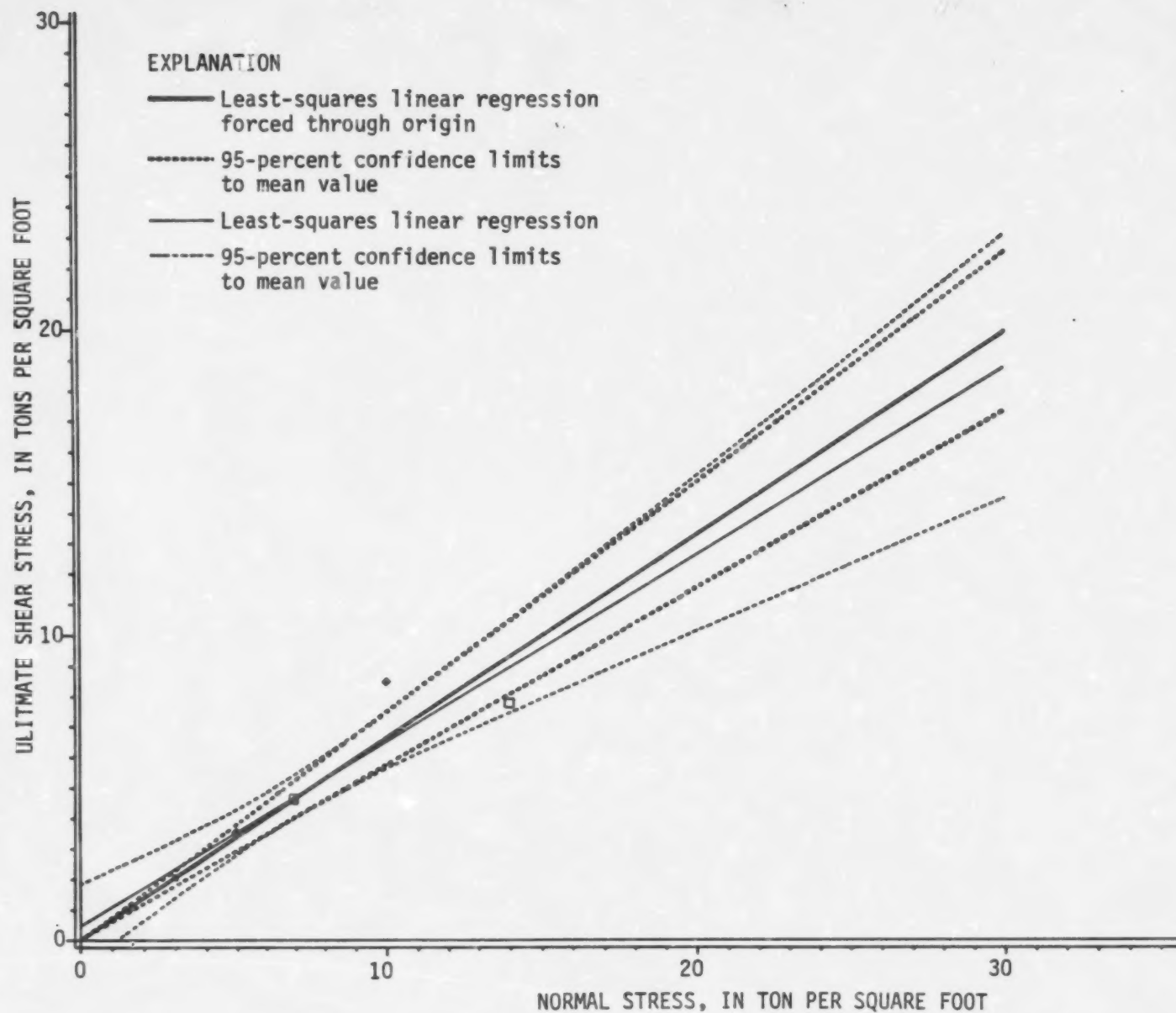


FIGURE 11b.--Results of direct shear-strength tests on the ancestral dacite unit of the avalanche debris from various sites: ultimate strength.

GROUND-WATER CONDITIONS

In July 1983, the Geological Survey installed 11 piezometers in the South Fork Castle Creek blockage to determine ground-water levels. Water-level measurements taken on September 20, 1983, (after sufficient time had been allowed for the wells to recover from the effects of drilling and development) show that a ground-water mound exists under the crest of the blockage (fig. 12). Water levels in the mound were as much as 22 feet above lake level at this time. Depth to water below the crest of the blockage in September 1983 ranged from about 60 to 20 feet, the greatest depth to water occurring in the northwestern part of the blockage and the least in the southeastern part. The fact that water levels in the mound are above lake level indicates that water moves from the mound into the lake and toward Castle Creek.

Ground-water levels in the blockage can be expected to fluctuate seasonally as the factors that affect ground-water recharge and discharge vary, but the absence of water-level measurements before July 1983 precludes definite determinations of the amplitude of the changes. However, the timing of fluctuations should be similar to that observed in a similar blockage that created Coldwater Lake, where water levels have been measured in piezometers since July 1981. This lake is 2 miles north of South Fork Castle Creek Lake and on the opposite side of the North Fork Toutle River valley (fig. 1). Water levels in the Coldwater blockage fluctuated seasonally, with annual highs in May and June and lows in September through October (fig. 13). The amplitude of these seasonal changes varies according to the location of the piezometer, but maximum changes of 15 feet have been observed along the crest.

The 2-year record of ground-water levels at the Coldwater Creek blockage also showed a net annual increase in water levels—35 feet from August 1981 to August 1982 and 15 feet from August 1982 to August 1983. This indicates that discharge from the ground-water system in the Coldwater blockage has yet to equilibrate to natural recharge; this is an important consideration in analyzing the stability of the South Fork Castle Creek blockage. Because slope stability varies indirectly with ground-water level, seasonal changes and the potential for annual increases in water level in the South Fork Castle Creek blockage are important. Water levels shown in figure 12 can be assumed to be near their seasonal low and were used to form "baseline conditions" for the stability analyses that follow. Stability analyses for higher ground-water levels were also made and are discussed in the next section.

The proximity of Coldwater Creek blockage to the South Fork Castle Creek blockage and their similarity of composition suggest that water-level changes similar to those at Coldwater blockage may be occurring at South Fork Castle Creek blockage. Owing to differences in blockage thickness, geometry, and other features, the magnitude of those changes may be different, however.

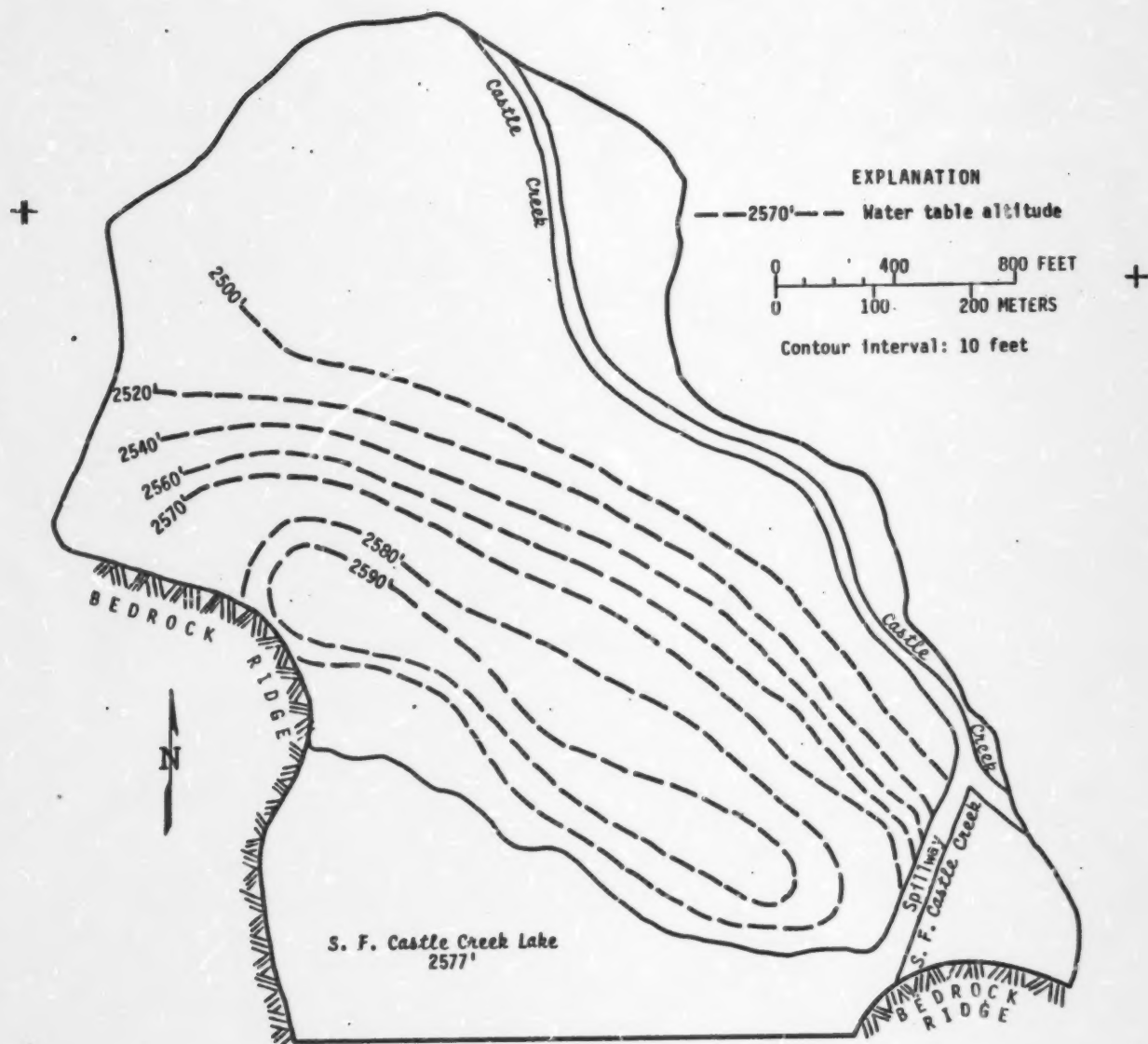


FIGURE 12.--Water-level contours for South Fork Castle Creek blockage,
September 20, 1983.

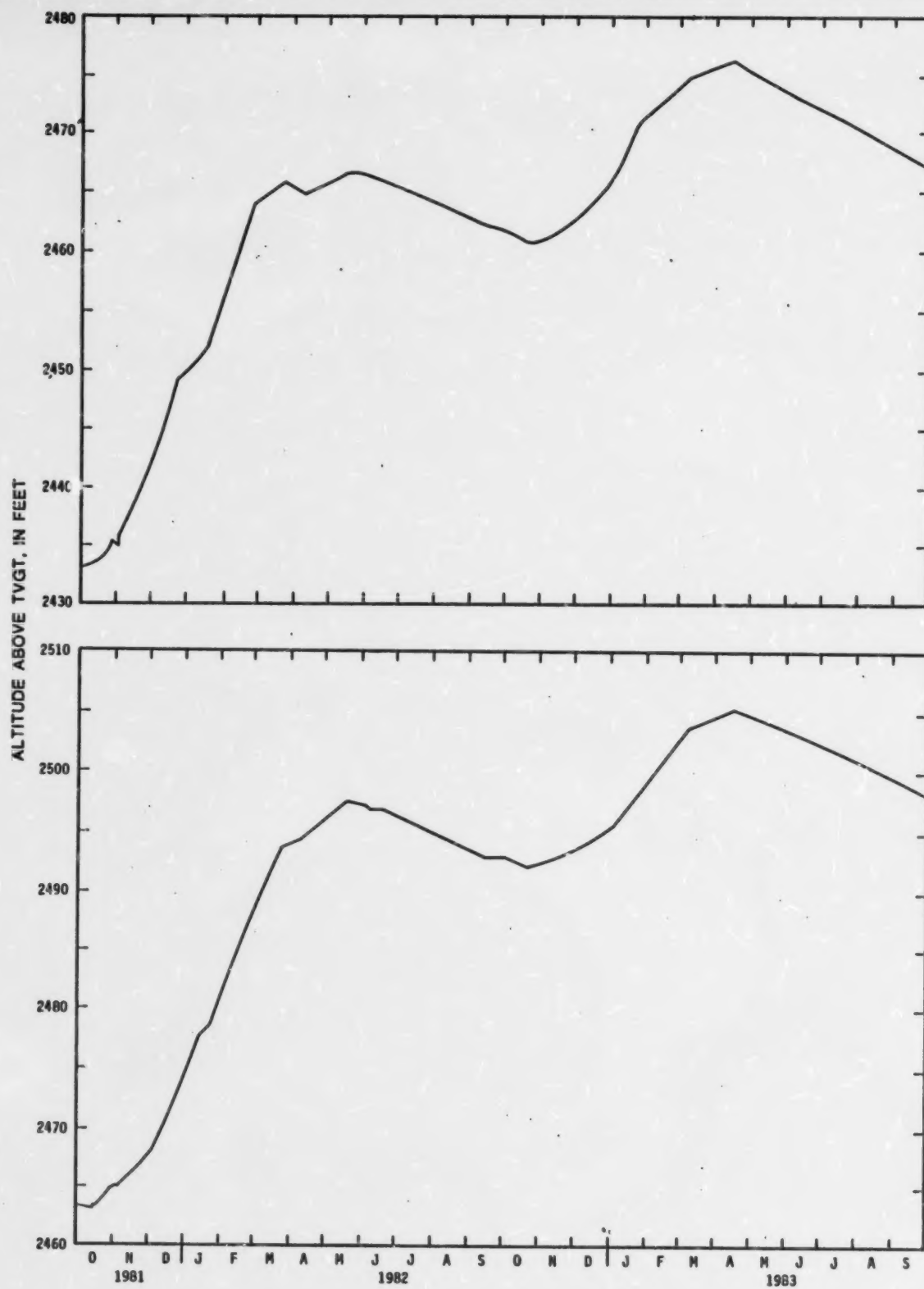


FIGURE 13.--Hydrographs for two selected piezometers at Coldwater Creek blockage.

STATIC SLOPE-STABILITY ANALYSIS

Factors of safety (F_s) were determined for five cross sections on the blockage by using a digital computer program, STABL3, prepared by the Joint Highway Research Project, Engineering Experiment Station, Purdue University. The program contains a subroutine that searches for slip surfaces most likely to fail. The program allows use of either the Modified Bishop Method or the Janbu Method of Slices for determining factors of safety associated with the model-predicted failure surfaces. The Modified Bishop Method was used throughout this study. As an independent check on the results, an analysis using the Morgenstern and Price Method was performed on a selected number of failure surfaces generated by STABL3; the resultant factors of safety were virtually identical (W. K. Smith, oral commun., 1982).

Modeled Cross Sections and Assumptions

Four of the five cross sections tested are on the downstream side of the blockage, the area from the blockage crest toward Castle Creek (fig. 14). Of these, the three (AA', BB', and CD) on the western part of the blockage, where downstream surface relief is greatest, are representative of downstream areas most susceptible to slope failure. The fourth (GG') is representative of the eastern part of the blockage, where overall downstream relief is low. Surface geology, configuration of the pre-eruptive surface, and ground-water levels for September 8, 1983, were determined for these sections (fig. 15a-d). The modern dacite, andesite, and basalt unit is the predominant geologic unit in all four cross sections.

Because slopes and subsurface conditions along the upstream side of the blockage, and the profile from the crest toward South Fork Castle Creek Lake, are generally uniform, one cross section, CF, was used to investigate the potential for slope failure in the upstream direction (fig. 15c).

At each cross section except GG', the factor of safety was determined for six different conditions (four for GG'). In all cases, wet and saturated unit weights of 105 and 125 lb/ft³, respectively, were assumed. These estimates were made before the field and laboratory test programs were completed, and the assumed unit-weight values are now considered low. A sensitivity analysis was conducted to examine the influence of unit weights on predicted factors of safety. Extreme values for unit weights produced a change in factor of safety no greater than 0.1.

A friction angle of 35 degrees was used for all analyses. This value is probably conservative because it approximates for material from the modern dacite, andesite, and basalt unit the laboratory ultimate rather than the peak (or some intermediate) condition, and the laboratory values ignore strength contributions from larger clasts and from moderate compaction. Because the ultimate friction angle for the blast pyroclastic-flow deposit and ancestral dacite unit is about 33.5 degrees, the use of 35 degrees may not be entirely conservative. Because the modern dacite, andesite, and basalt unit constitutes most of the blockage, 35 degrees is considered reasonable for analytical purposes.

Using the above assumption, cohesion was set to zero and stability was determined at each cross section for three positions of the water table: (1) the measured water level for September 1983; (2) the September 1983 water level plus 25 feet; and (3) the water level at land surface. Cohesion was next set to 200 lb/ft^2 and stability again determined for the three positions of the water table. At section GG', however, September 1983 water levels were about 20 feet below the crest, and therefore only two water level positions were used—the September 1983 water level and the water level at land surface—with values of cohesion at zero and 200 lb/ft^2 .

The program requires the definition of a lower boundary into which no generated failure surface will penetrate. The pre-eruption surface underlying the blockage was chosen as this boundary. Cross sections AA' and BB' are underlain by the bedrock ridge on the western side of South Fork Castle Creek valley (figs. 15a,b), so the assumption of non-penetration along those sections is valid. Cross sections DF and GG' are underlain by pre-historic unconsolidated volcanoclastic deposits, and the assumption that this material represents a boundary into which no generated failure surface could penetrate may not be valid. However, results of the computer analysis along these sections indicate that the surfaces most likely to fail are above the pre-eruption surface; potential failure along these sections is therefore independent of the nature of the pre-eruption surface.

Cross sections AA' and BB' terminate near the ridge bordering the western side of the lake. Slope failure along these sections would not result in a lake breakout unless this failure weakened the remaining blockage or unless it was accompanied by a failure back into the lake near these sections. The second possibility does exist, and therefore stability in the areas of cross sections AA' and BB' is evaluated.

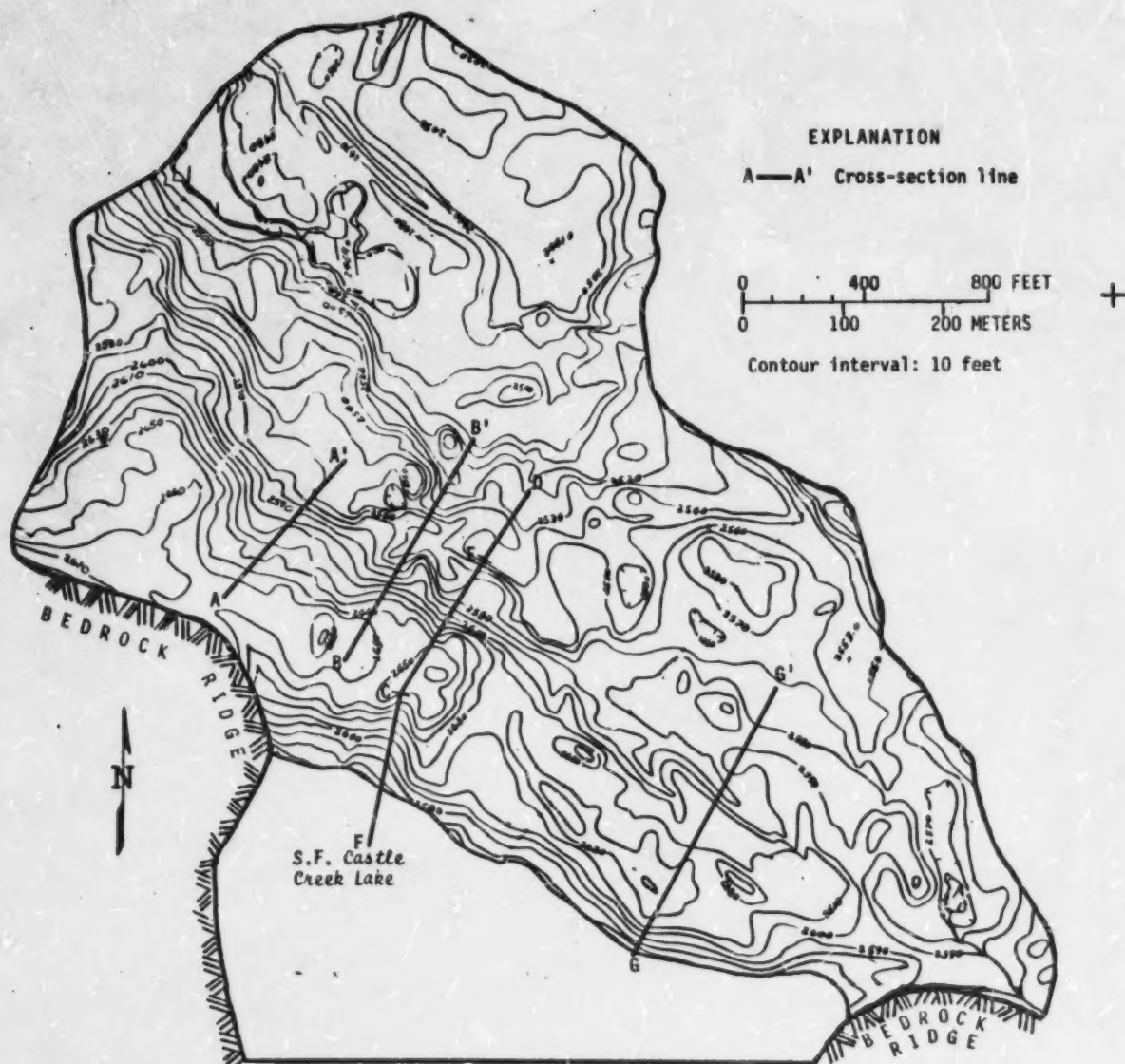


FIGURE 14.--Location of cross sections on South Fork Castle Creek blockage that were analyzed for slope stability.

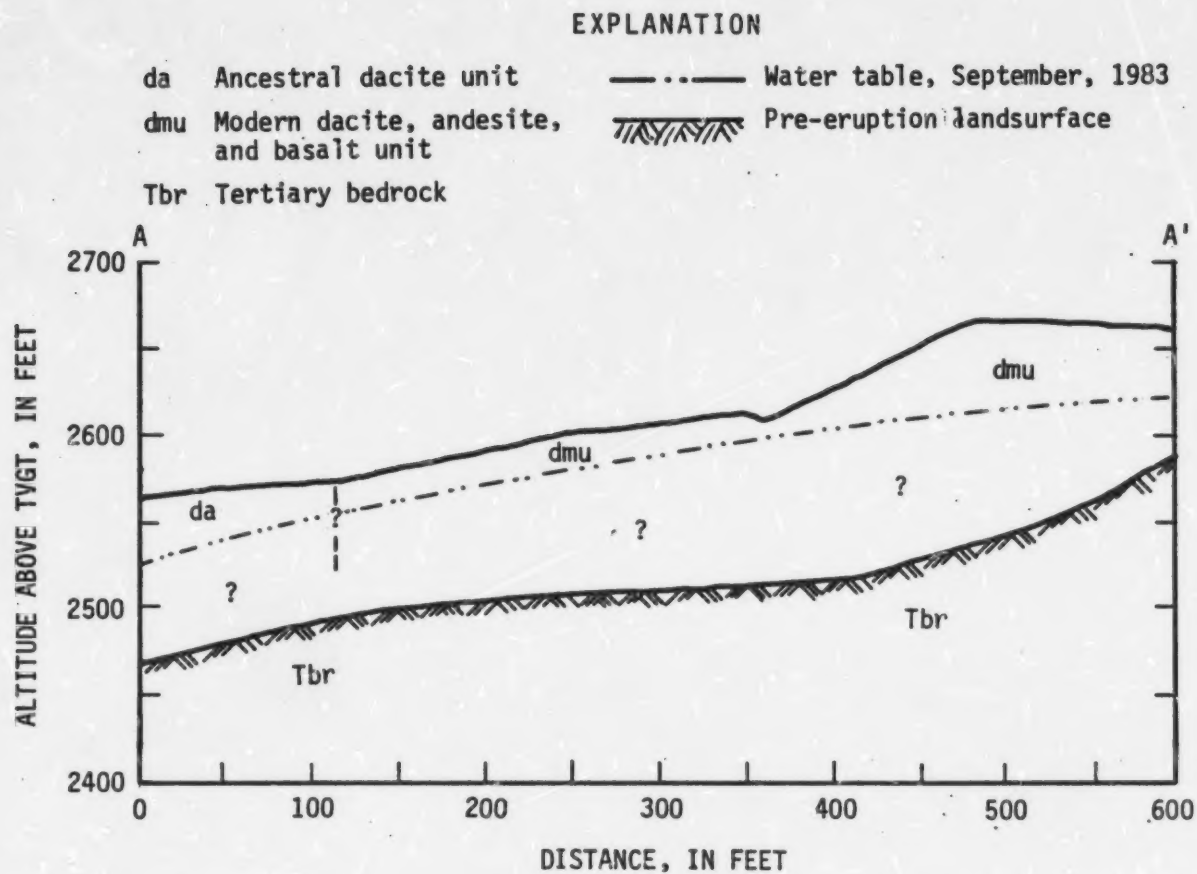


FIGURE 15a.--Geology and September 1983 water levels at cross section AA'.

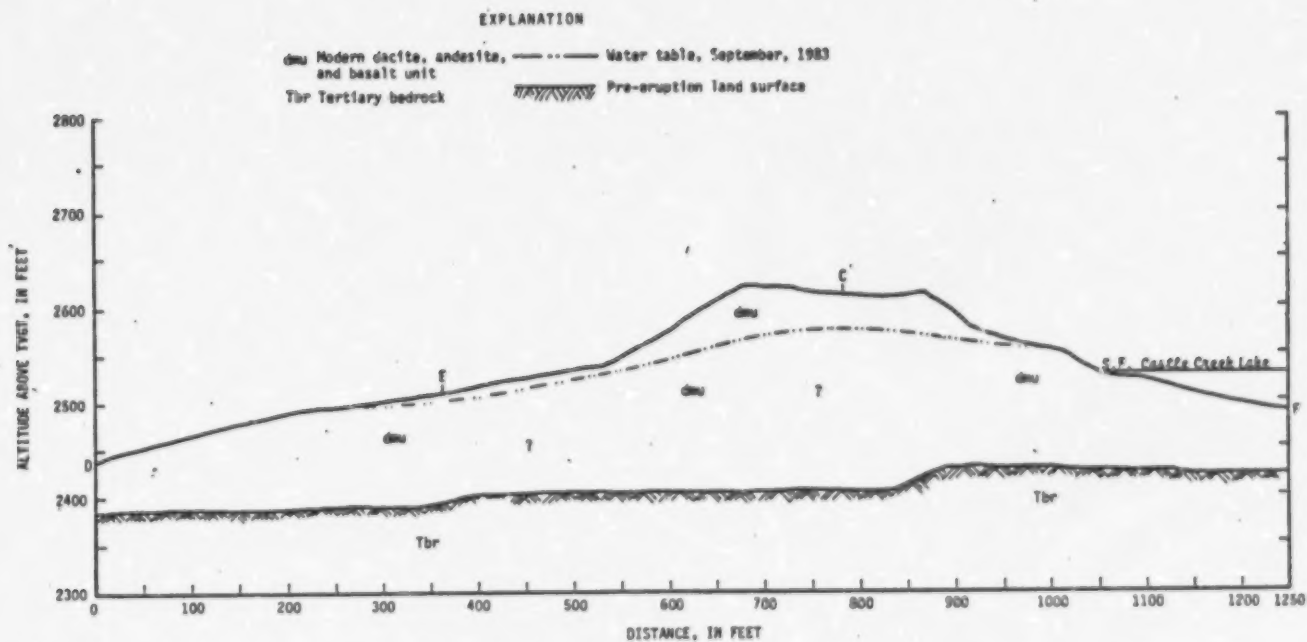


FIGURE 15c.--Geology and September 1983 water levels at cross sections CD, CE, and CF.

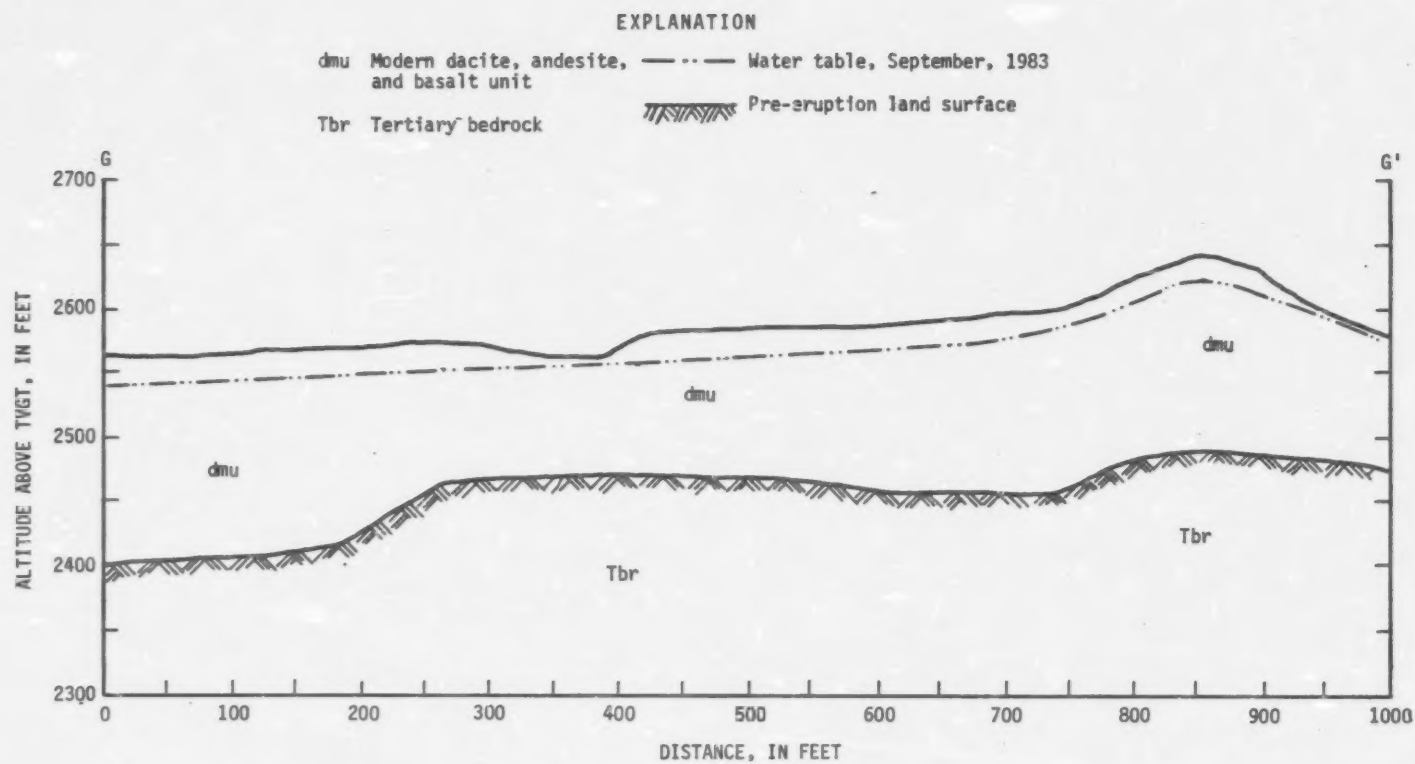


FIGURE 15d.--Geology and September 1983 water levels at cross section GG'.

Results of Static Slope-Stability Analysis

For each set of physical conditions used in a model simulation, the program generated 100 failure surfaces and calculated the factor of safety, F_s , for each surface. It also identified the surface with the lowest factor of safety, F_s^* , hereafter referred to as the critical failure surface. Model-predicted F_s^* values are summarized in table 3 for each set of physical conditions simulated at the cross sections. An F_s value less than or equal to 1.0 is considered to indicate potential instability. Although F_s values predicted by the model should be considered reasonable approximations of the actual values, some uncertainties about material properties and analysis exist, and therefore factors of safety of 1.2 or less are interpreted as identifying sections of potential instability.

Several general trends are apparent from the results of the static stability analysis. First, as ground-water levels rise factors of safety for potential failure surfaces decrease, indicating that the blockage becomes less stable. This is illustrated in table 3. Second, rising ground-water levels also cause the range in values for the 10 lowest F_s surfaces to narrow (fig. 16), causing larger areas of the blockage to become unstable. Third, for a given water level, analysis using a cohesion of 200 lb/ft² shows an average increase in F_s^* of 0.3 over the F_s^* obtained with zero cohesion.

Results of the static analyses indicate that massive slope failures on the blockage from gravitational forces are unlikely when the ground-water table is at or near its September 1983 position. F_s^* values for failure surfaces at all cross sections are above 1.2 for this condition. Potential failure is predicted on the blockage with ground-water levels 25 feet above September 1983 levels and zero cohesion. With the water table at land surface and zero cohesion assumed, additional cross sections on the blockage are predicted to fail. These failures alone are not expected to initiate lake breakout because a portion of the blockage is left intact above lake level. Only cross sections BB' and GG' are stable for all three positions of the water table. The most conservative analyses for these sections, using a water level at land surface and zero cohesion, are shown in figures 17a, b.

The occurrence of potential failure surfaces predicted by the model with the water table 25 feet higher than for September 1983 is dependent upon the value used for cohesion. With an assumed cohesion value of 200 lb/ft², no failures are predicted. However, when zero cohesion is assumed slope failures are predicted along cross sections CE and CF (table 3 and fig. 18). The critical failure surface on cross section CE, with an F_s^* value of 1.2, extends 45 feet behind the crest of the blockage and to a depth of 10 feet below lake level. On cross section CF the critical failure surface has a F_s value of 1.1. Two other potentially unstable shallow failure surfaces occur with F_s values equal to 1.1 and 1.2. Neither surface penetrates into the blockage below lake level. Such failures occurring along both cross sections simultaneously would not result in lake breakout because a substantial part of the blockage above lake level would be left intact.

With the water table at the land surface, potential failure surfaces are predicted at cross sections AA', CE, and CF with both zero and 200 lb/ft² cohesion values. At cross section AA' the predicted failure surfaces are shallow and don't extend below lake level for either value of cohesion (figs. 19a,b). Therefore, these failures would have little influence on short-term blockage stability. At cross section CE, potential failure surfaces extend a maximum depth of 25 feet below lake level and 100 feet behind the blockage crest for zero cohesion (fig. 20a) and 50 feet behind the crest for 200 lb/ft² cohesion (fig. 20b). At cross section CF, potential failure surfaces are shallow, and none extend below lake level with a 200 lb/ft² cohesion value. However, with a zero cohesion value, a potential failure surface of 1.2 extends about 30 feet below lake level and 50 feet behind the blockage crest. The critical failure surface does not extend below lake level and has an F_s^* value of 0.6. The potential failure surfaces along cross sections CE and CF that are predicted with both the water table at land surface and zero cohesion, and that have F_s values <1.2, constitute a significant mass of the blockage, and some extend well below lake level. However, failure along both surfaces with F_s values of 1.2 (shown in figure 20a) would still leave a substantial part of the blockage intact and above lake level. Thus, lake breakout is not predicted for initial slope failures on the blockage, regardless of the position of the water table.

Retrogressive Failure Analysis

Retrogressive slope failure was analyzed for composite cross section DF on that portion of the blockage remaining after initial slope failures, using water levels 25 feet higher than September 1983 and at land surface. The analysis includes the following assumptions, which are considered to be conservative: (1) The material above the initial and all successive sliding surfaces is removed from the blockage; (2) Retrogressive sliding occurs along the deeply penetrating surfaces that have F_s values <1.2 and that encompass the greatest amount of blockage material; and (3) Each slide mass will not interfere with or influence the movement of successive slides. Zero cohesion was assumed in all analyses.

With a 25-foot rise in the water table above its September 1983 position, retrogressive analysis indicates that the blockage would remain above lake level, thus precluding lake breakout (fig. 21). With the water table at land surface, the analysis for retrogressive failure indicates that the blockage could conceivably be lowered below lake level and thereby cause lake breakout (fig. 22).

The degree of mobility assumed for breakout from retrogressive failure is considered to be unlikely because the blockage is composed of moderately compact, poorly sorted debris, contains large clasts, and is subjected to moderate confining pressure. Slope failures are more likely to occur as debris slides, slumps, and slump flows, with slow flowage at the toe of the displaced mass. Driving forces decrease and resisting forces increase as a function of displacement on deep-seated, curved slide surfaces, so displacements are limited and would seldom exceed a value of approximately 100 feet. Movements of this order of magnitude are not sufficient to reduce the blockage crest to or below lake level. Therefore, the possibility of actual lake breakout from retrogressive slope failure is considered remote.

TABLE 3.--Physical properties, South Fork Castle Creek blockage and other debris avalanche sites

Sample number	Geologic unit	Specific gravity minus No. 4	d _{min} (lbs/ft ³)	Field water content (pct)	Void ratio ¹	Porosity ¹ (pct)	d _{min} (lbs/ft ³)	d _{max} (lbs/ft ³)	D _r (pct)	c' (ton/ft ²)	φ' (degree)	φ* (degree)
<u>South Fork Castle Creek Blockage</u>												
82-826-1	MDL ²	2.70	99.3	5.6	0.67	40	117.1	136.3	0	--	--	--
82-826-2	MDL	2.70	94.3	3.0	.75	43	115.0	134.8	0	--	--	--
82-827-6	MDL	2.57	89.9	8.2	.84	46	82.4	92.2	55	0.10	38	38.5
82-827-7	MDL	2.60	93.6	9.3	.72	44	97.2	113.6	0	.25	35	36
8-827-8	MDL	2.66	108.6	5.2	.52	34	113.0	132.4	0	.20	36	37
82-826-3	Ancestral dacite	2.68	90.5	3.4	.83	45	109.1	129.0	0	--	--	--
82-826-4	Blast pyroclastic flow	2.69	126.1	6.2	.31	24	136.7	127.6	93	.50	41.5	44
<u>Debris avalanche, various sites</u>												
Dx5-3	Modern dacite	2.69	115.4	--	--	--	95.5	117.0	95	.20	33.5	35
Dx3-20	Ancestral dacite	2.71	129.8	--	--	--	108.2	137.3	26	.40	30	35
Dx5-24	Ancestral dacite	2.75	116.1	--	--	--	85.2	112.6	100	0	35	35
COE	Ancestral dacite	2.73	130.0	38.0	.31	24	108.1	132.6	91	2.14	36.9	52
COE	Ancestral dacite	2.73	118.9	--	.43	30	107.5	128.5	--	.23	44.9	45

NOTES:

¹calculations using average specific gravity 2.65²MDL modern dacite and lava unit.³Assumed water content.

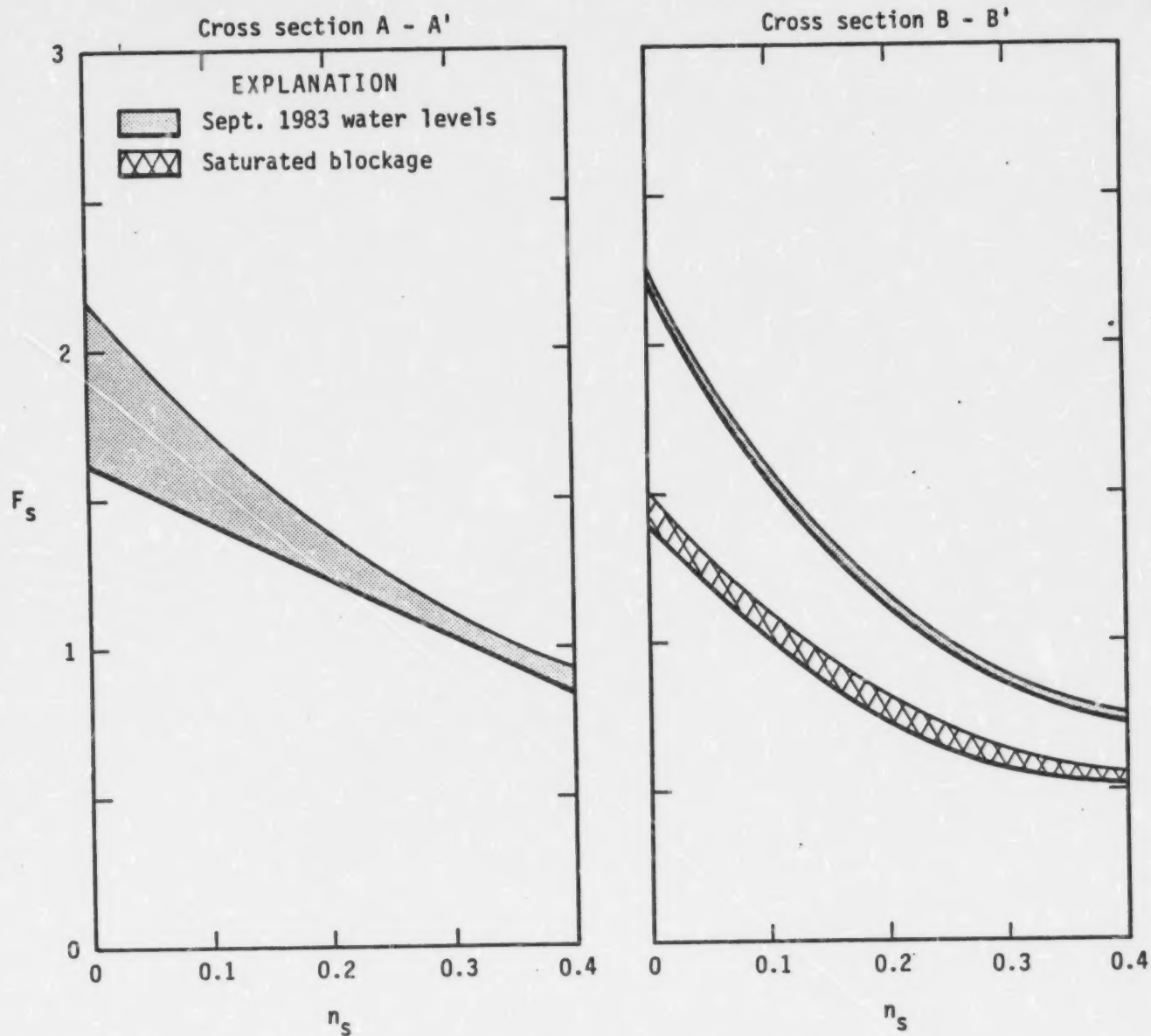


FIGURE 16.--Graphs showing variation of factor-of-safety values (F_s) versus seismic coefficients (n_s) for selected water levels at all cross sections.

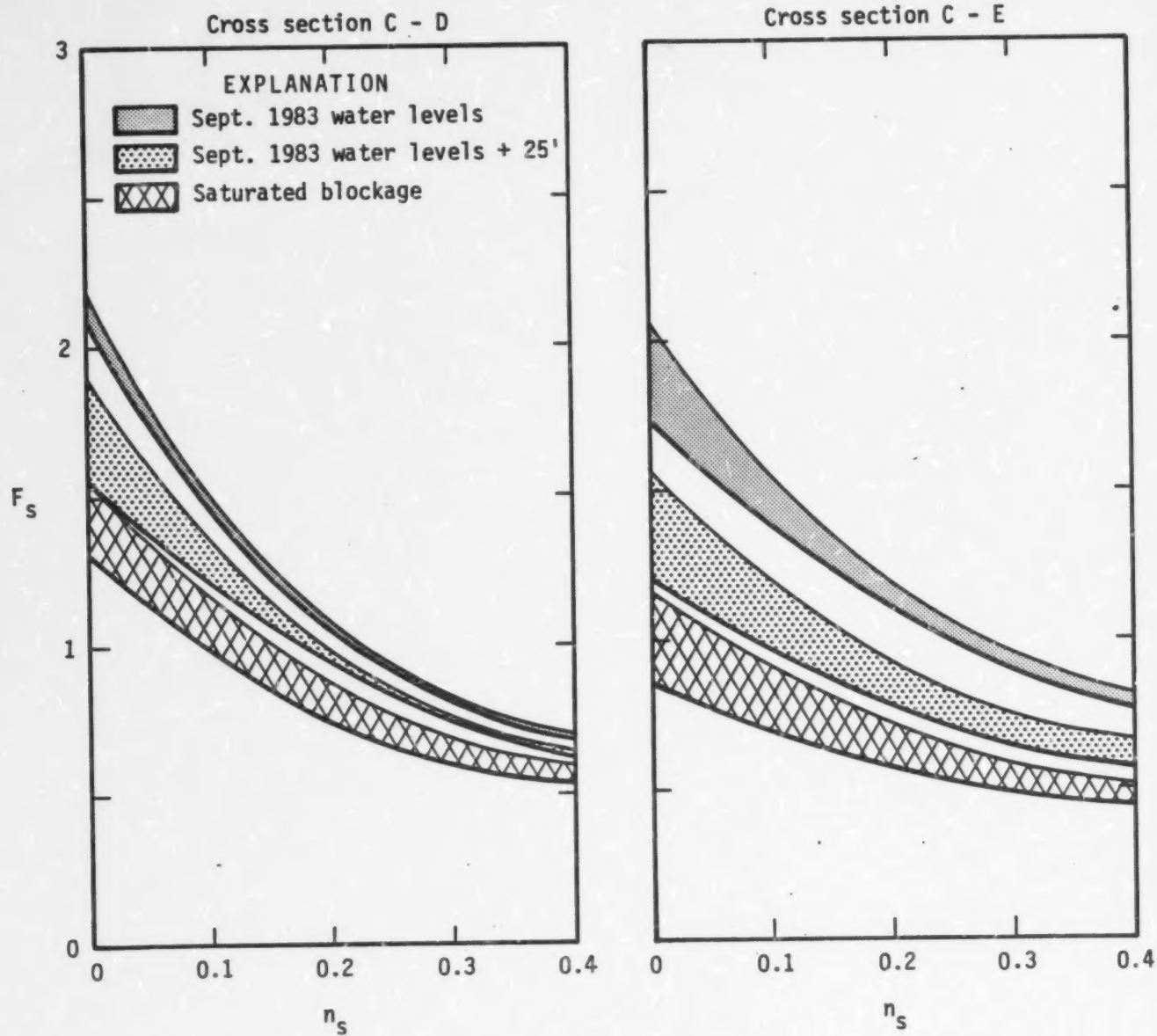


FIGURE 16.--Continued.

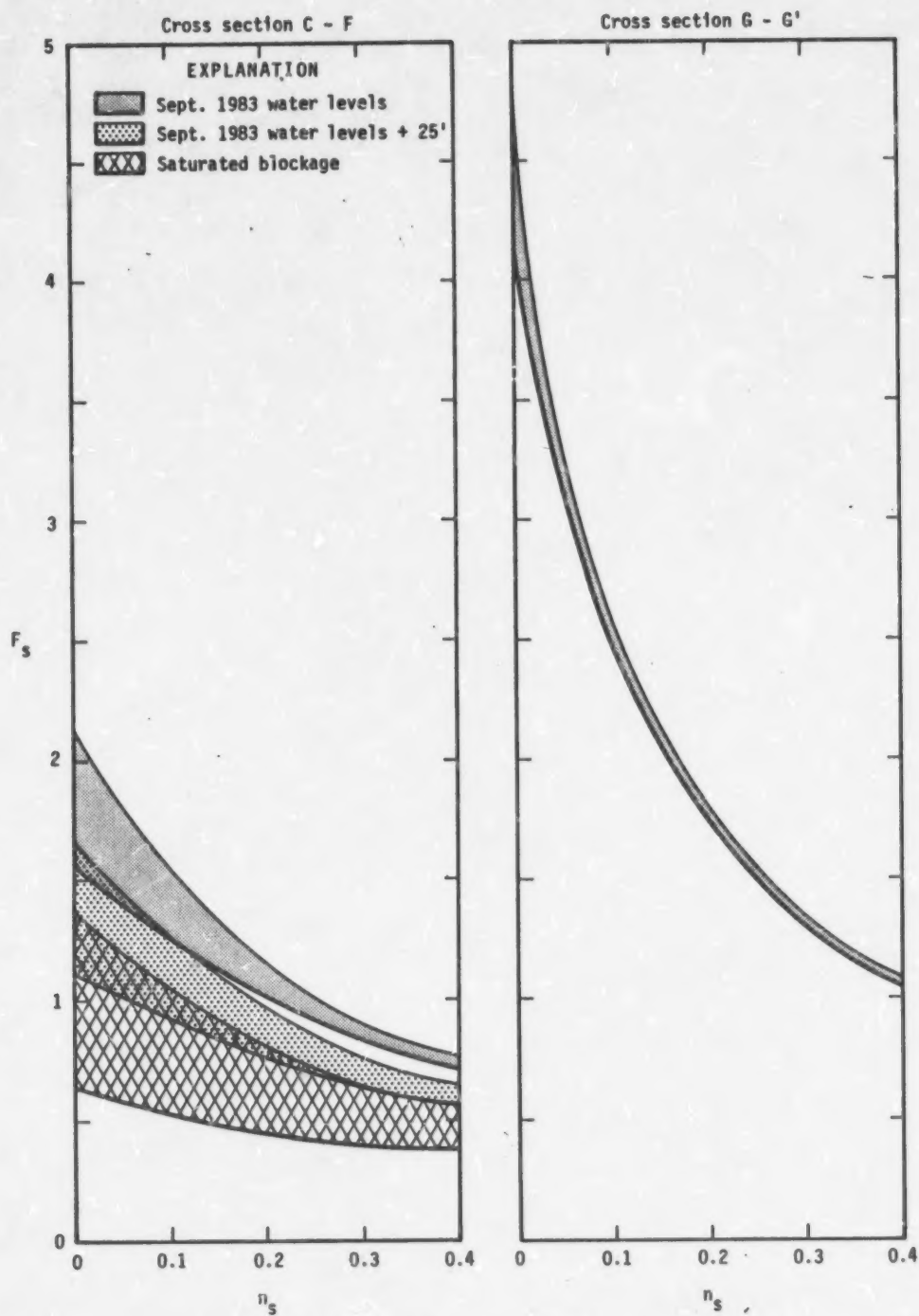
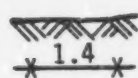


FIGURE 16.--Continued.

EXPLANATION



Pre-eruption land surface

Critical failure surface and factor of safety

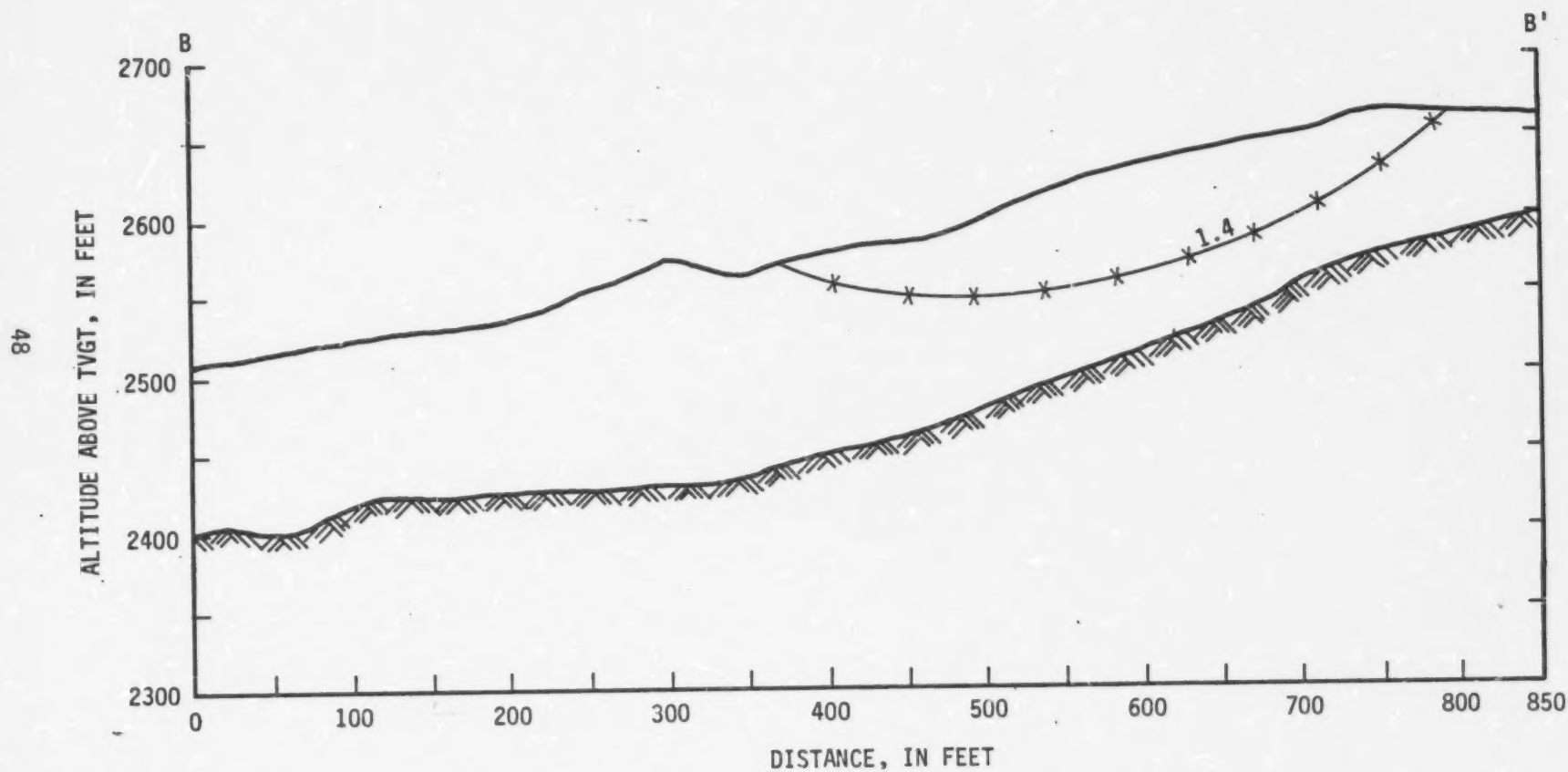


FIGURE 17a.--Critical failure surfaces predicted for cross section BB'.

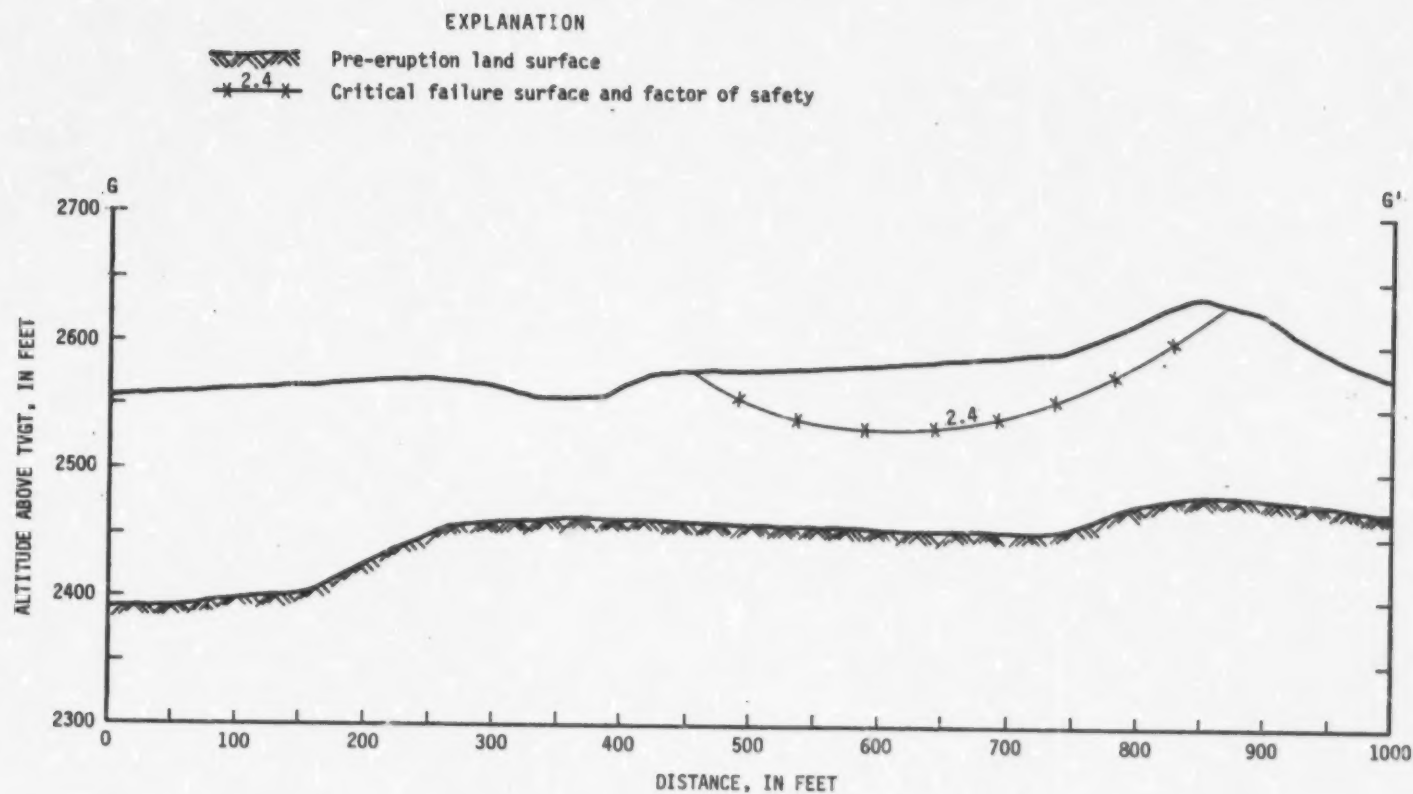


FIGURE 17b.--Critical failure surfaces predicted for cross section GG' with water table at land surface and zero cohesion.

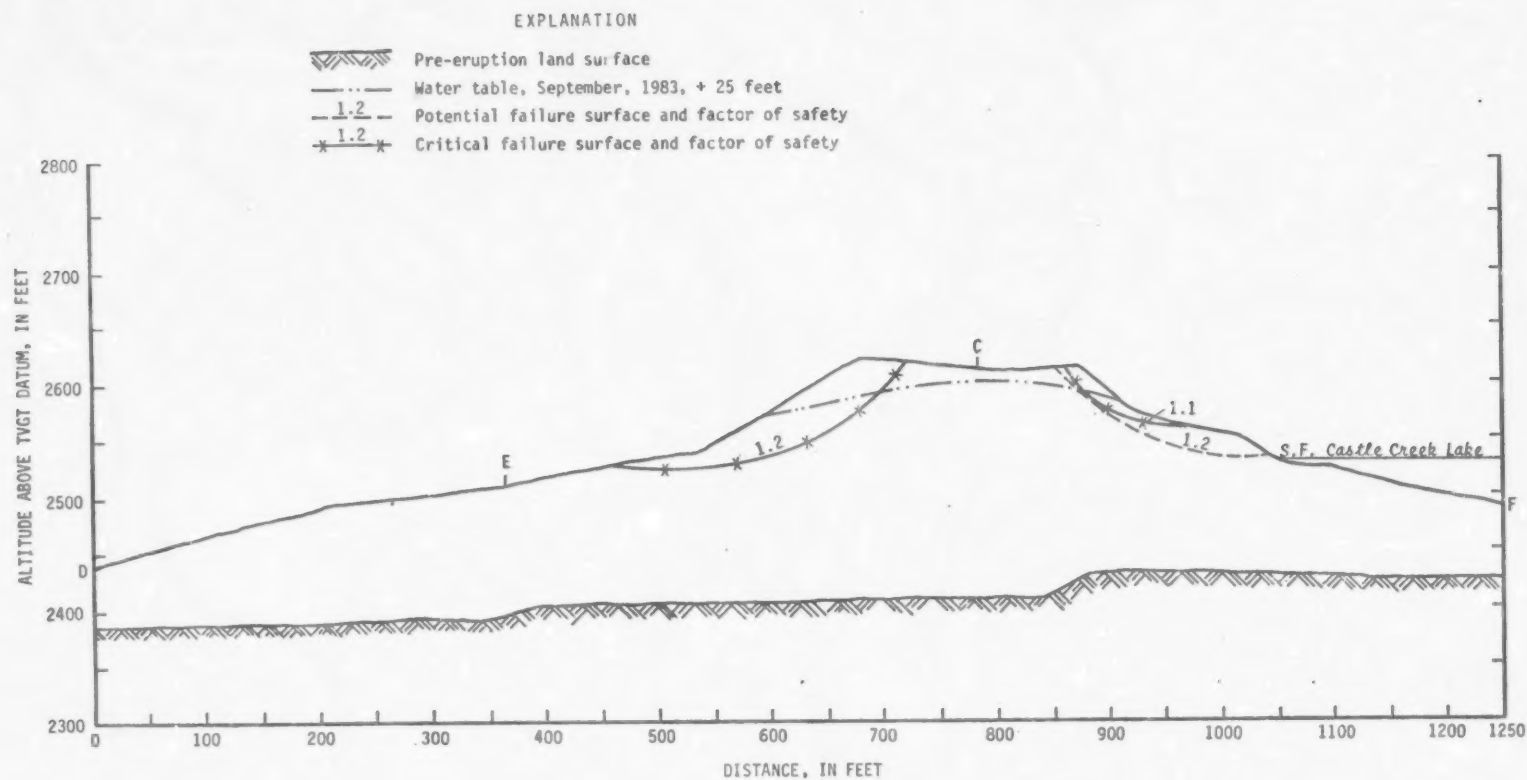


FIGURE 18.--Predicted failure surface and potential failure surfaces encompassing the largest section of the blockage for cross sections CE and CF with water table 25 feet above September 1983 levels and zero cohesion.

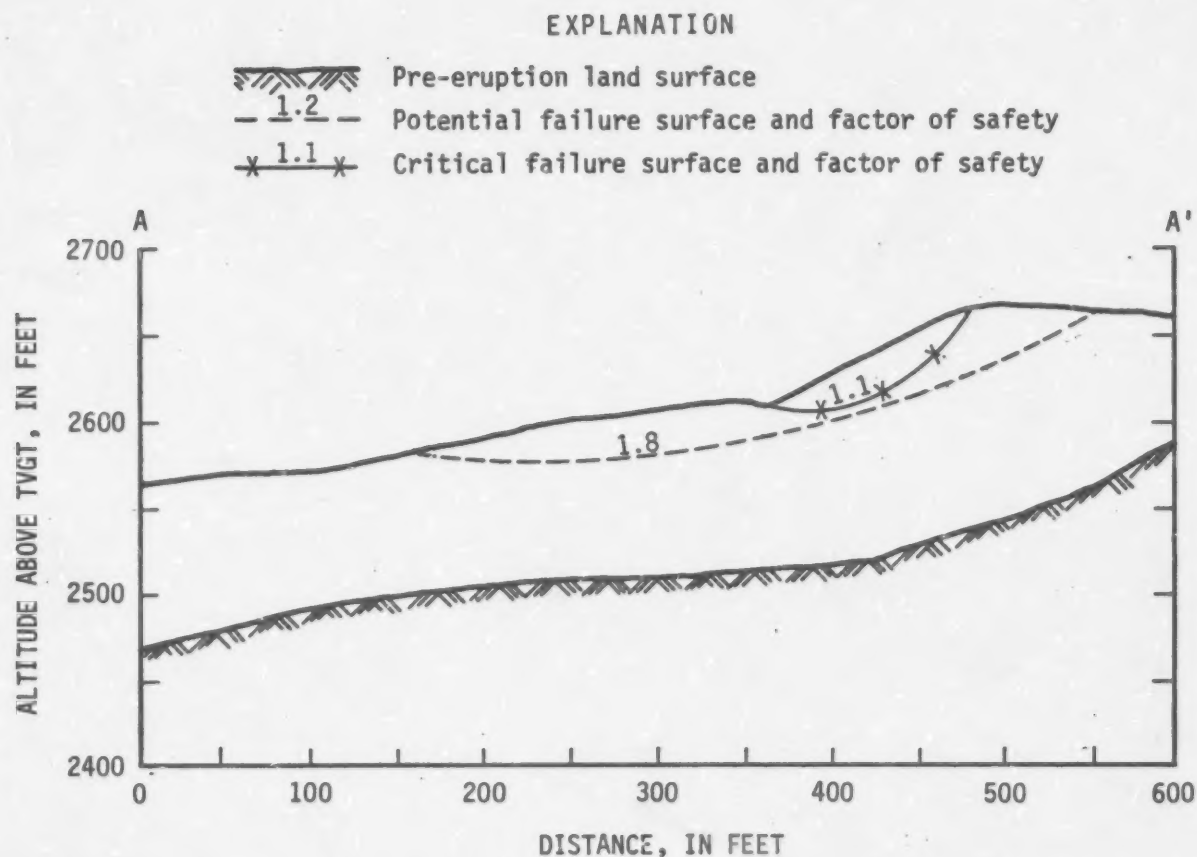


FIGURE 19a.--Critical failure surfaces predicted for cross section AA' with water table at land surface and 200 lb/ft² cohesion.

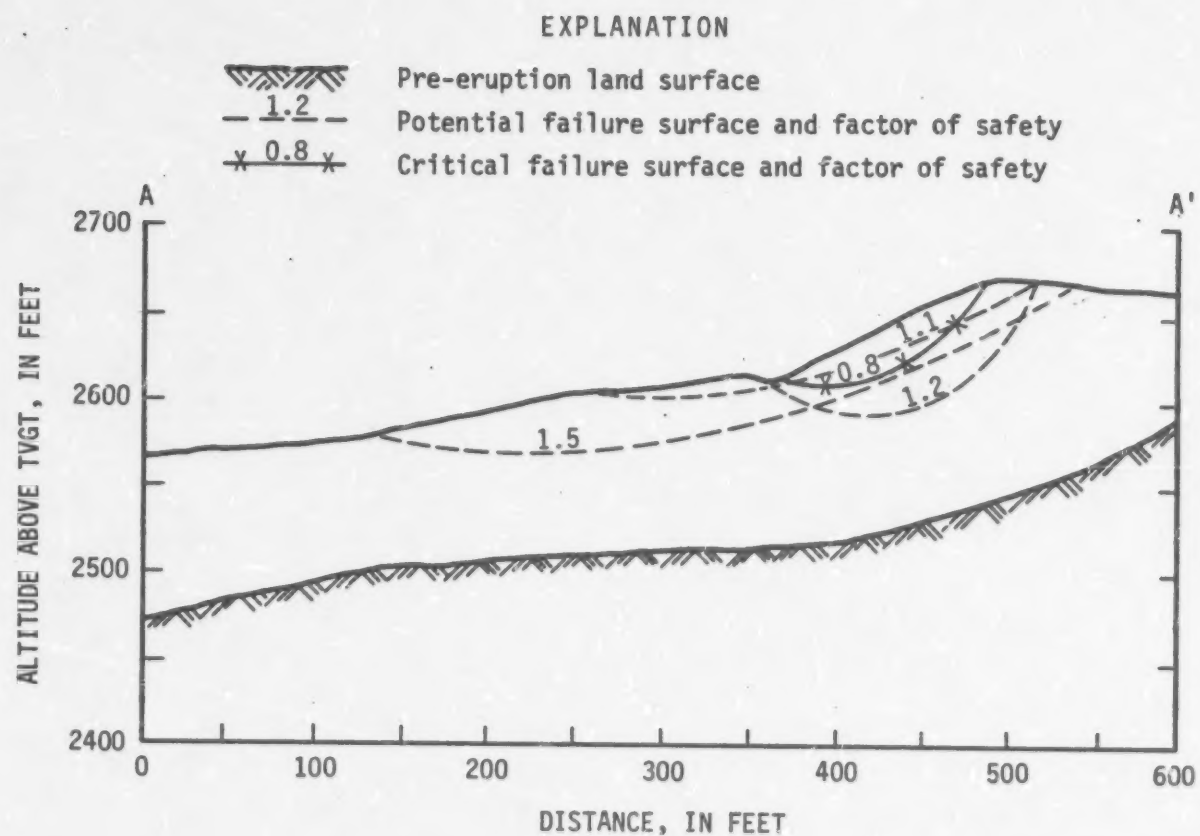


FIGURE 19b.--Critical failure surfaces predicted for cross section AA' with water table at land surface and zero cohesion.

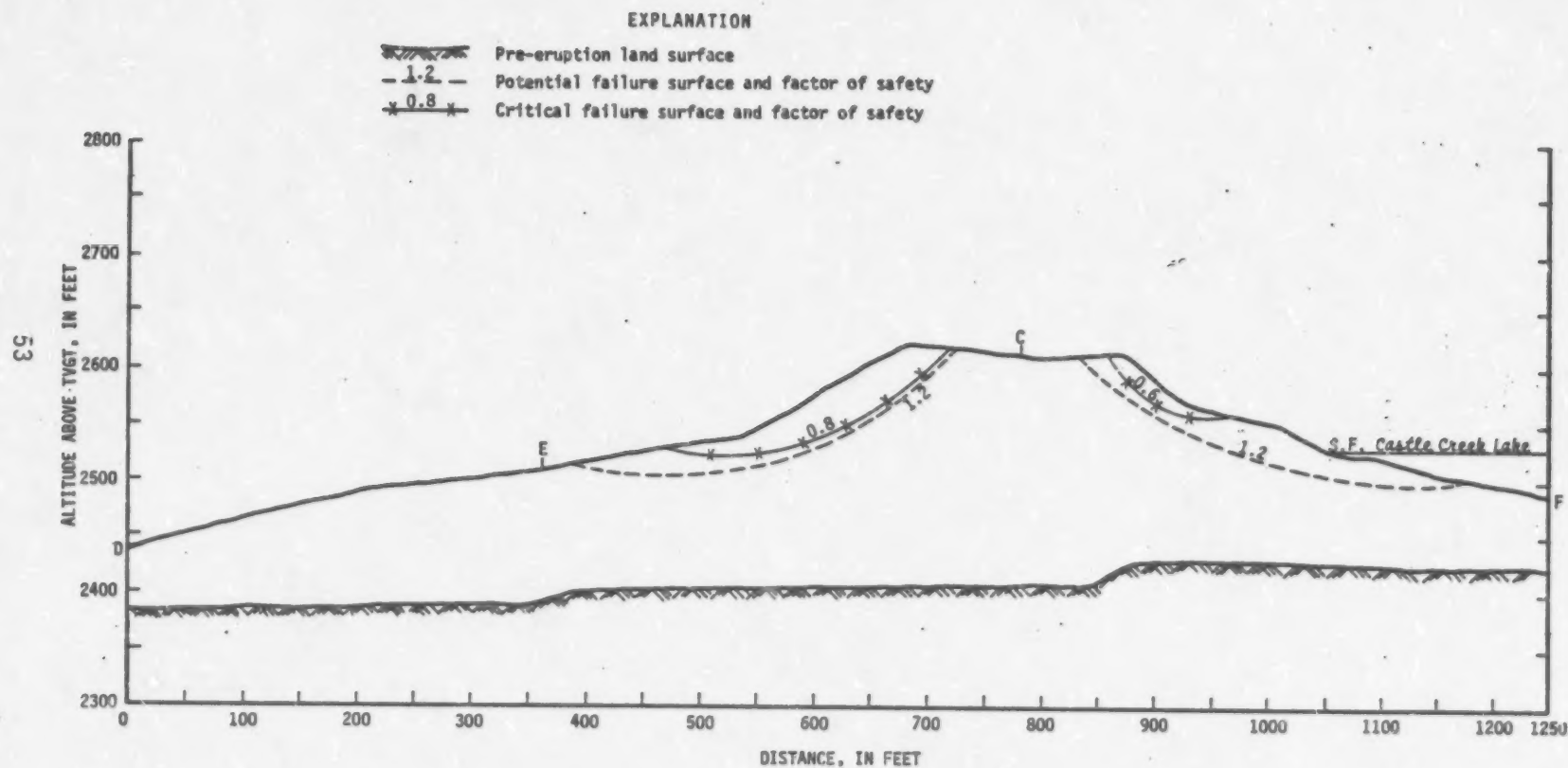


FIGURE 20a.--Predicted failure surface and potential failure surfaces encompassing the largest section of the blockage for cross sections CE and CF with water table at land surface and zero cohesion.

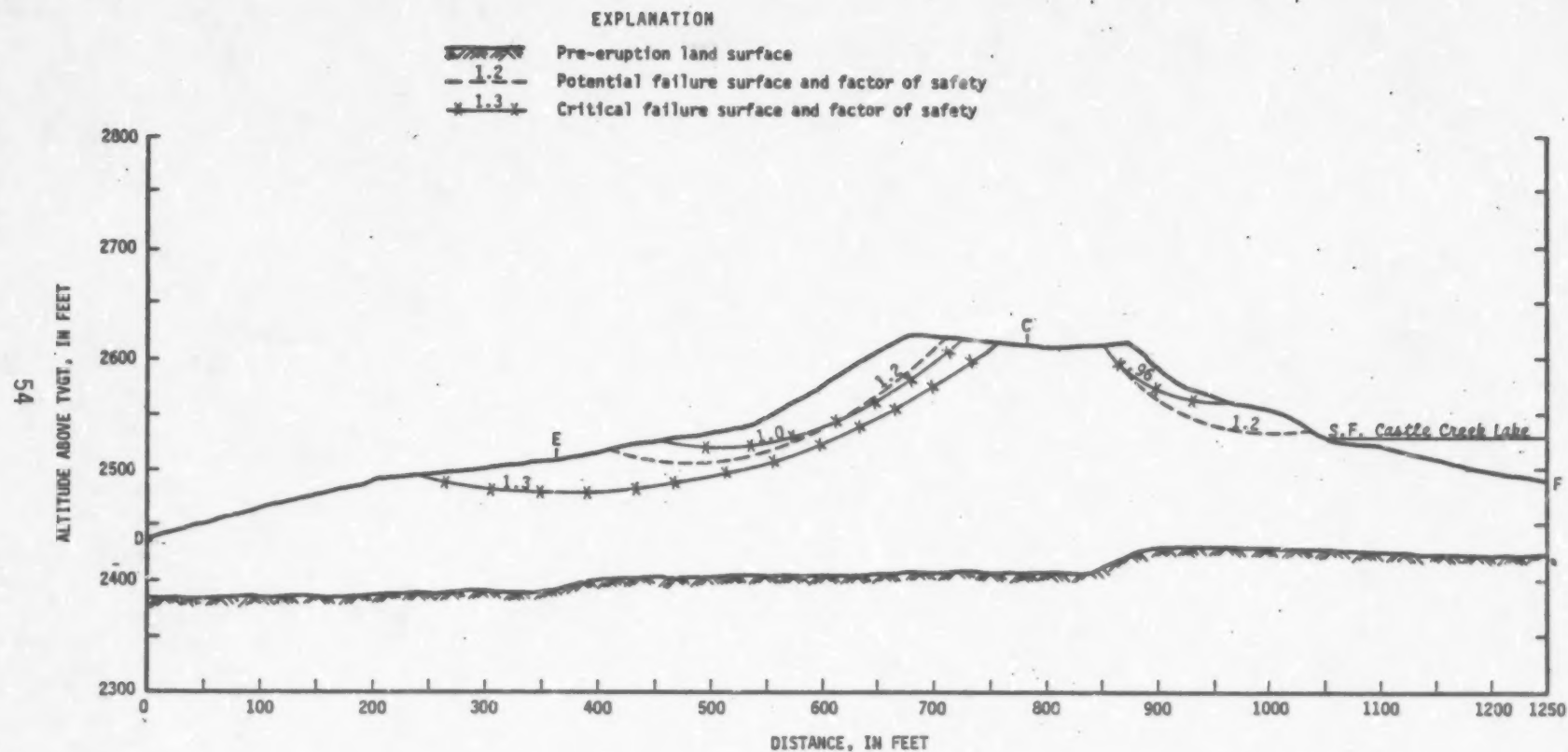


FIGURE 20b.--Predicted failure surface and potential failure surfaces encompassing the largest section² of the blockage for cross sections CE and CF with water table at land surface and 200 lb/ft².

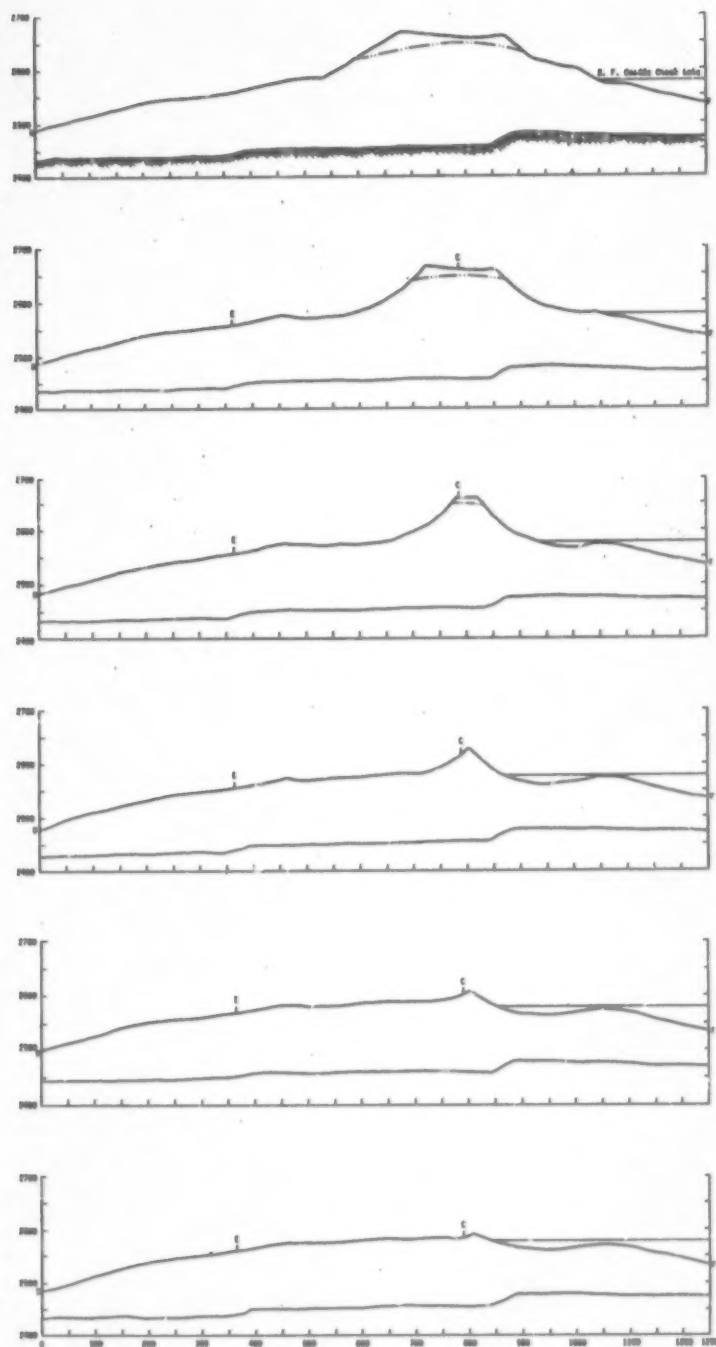


FIGURE 21.--Predicted results of retrogressive slope-failure analysis on cross sections CD and CF with September 1983 water levels plus 25 feet and zero cohesion.

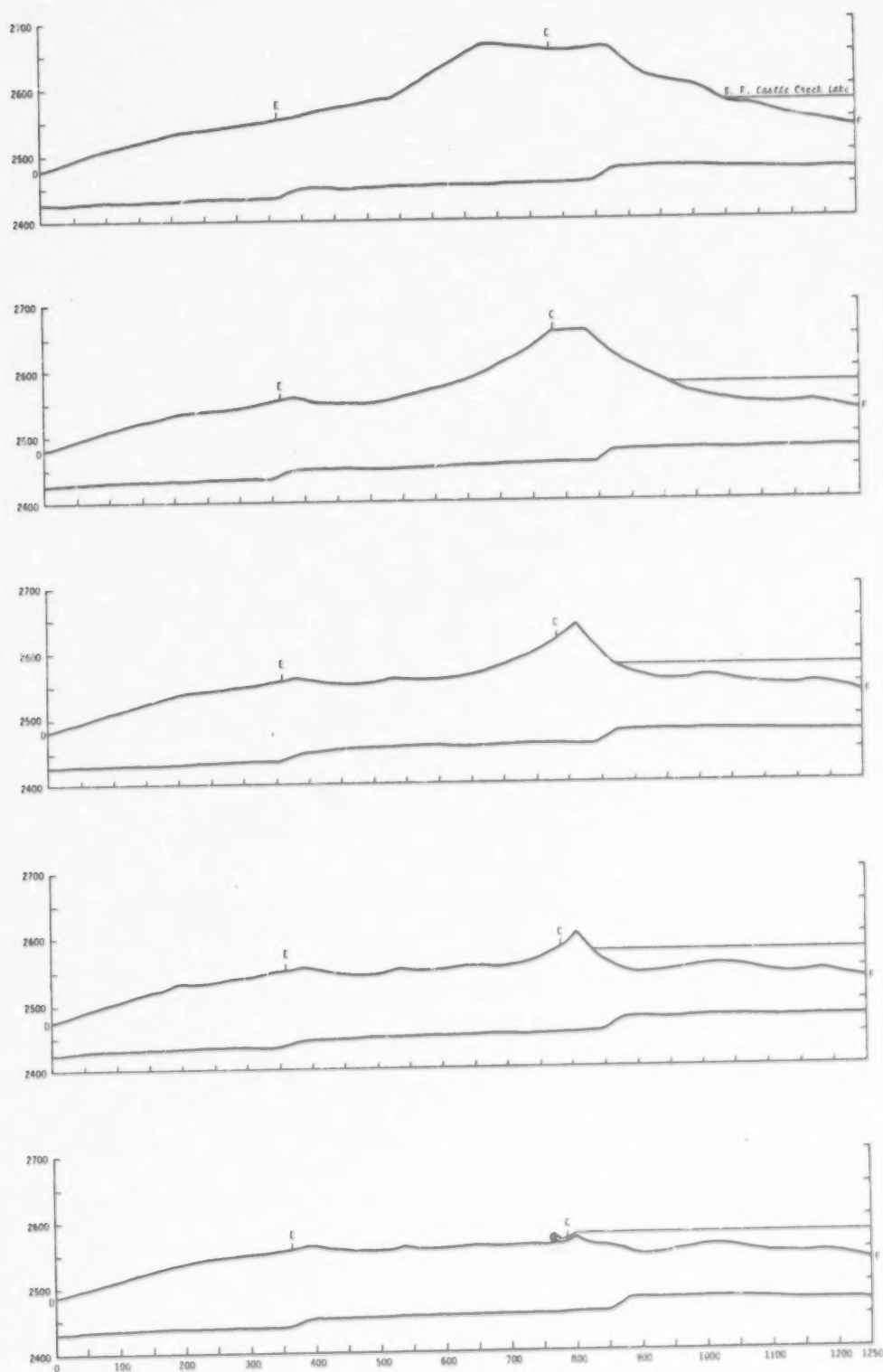


FIGURE 22.--Predicted results of retrogressive slope-failure analysis on cross sections CD and CF with water table at land surface and zero cohesion.

SEISMIC HAZARD

Estimates of the seismic hazard at South Fork Castle Creek blockage are based primarily on information about the St. Helens seismic zone (SHZ), which passes within several miles of the blockage (fig. 1). Defined by small-to-moderate-magnitude (2.5 to 5.5) earthquakes, the SHZ is interpreted as a 60-mile-long fault zone capable of generating a moderate-to-large-magnitude, shallow (crustal) earthquake (Weaver and Smith, 1983). Earthquake focal mechanisms along the SHZ indicate nearly vertical right-lateral, strike-slip faulting with the preferred fault planes striking north-south. From these focal mechanisms, the direction of maximum compression is northeast, approximately parallel with the direction of plate convergence between the North American and Juan de Fuca Plates. The focal mechanism data suggest "locked" subduction, and this interpretation raises the possibility of a larger magnitude subduction earthquake (Weaver and Smith, 1983).

A magnitude 5.5 (local Richter magnitude) earthquake occurred on February 14, 1981, near Elk Lake, 6.5 miles north of the South Fork Castle Creek blockage (Grant and others, 1983). More than a thousand aftershocks up to magnitude 4.5 delineated a north-south-trending fault zone 4 miles long by 2 miles wide, ranging from 3 to 8 miles in depth. The probable low-stress drop of the main shock suggests that pre-existing stress levels were not extensively lowered and that another moderate earthquake may still occur near Elk Lake (Grant and others, 1983).

The occurrence of an earthquake larger than 5.5 magnitude along the SHZ must also be considered as a possibility. Using empirical regressions of magnitude with fault length (Mark and Buchanan, 1977), a magnitude 7 earthquake would correspond approximately with a rupture of 50 percent of the length of the SHZ. However, Weaver and Smith (1983) recognized that there is no reliable procedure for estimating a maximum magnitude for the 1983 circumstances, and they considered a magnitude 7 earthquake unlikely for two reasons. First, Mount St. Helens is in the middle of the zone and the zone may be discontinuous across the mountain. Second, the earthquakes are in a zone several miles wide in which no surface faulting has been found; therefore, the crustal earthquakes could involve rupture of short fault segments, say on the order of 6 miles. Weaver and Smith did not specify an expected maximum magnitude event, but did caution that the Elk Lake earthquake does not represent the largest possible event on the SHZ. Beaulieu and Peterson (1981), in an evaluation of potential hazards at a nearby nuclear site suggested that a maximum magnitude of 6.2 is more likely than one of magnitude 7.

The U.S. Army Corps of Engineers proposed a 6.8-magnitude design earthquake for their stability analysis of the Spirit Lake blockage (U.S. Army Corps of Engineers briefing, July 5, 1983, Portland, Oregon). This design earthquake would lie on the SHZ and have a near-source horizontal acceleration of 0.55 g, a shaking velocity of 1.8 ft/s, and duration of strong shaking of 30 seconds.

Earthquakes along the SHZ in the magnitude range of 6.2 to 6.8 are capable of producing peak horizontal accelerations of 0.55 g at the South Fork Castle Creek blockage (H. B. Seed, written commun., 1983), so this value seems reasonably conservative for seismic analysis of the blockage. For purposes of comparison, a magnitude 5 earthquake on the Spirit Lake segment of the SHZ could produce peak accelerations of 0.3 g for two or three loading cycles at the blockage.

Seismic History of the Blockage

Since its emplacement on May 18, 1980, the blockage has been subjected to three periods of shaking. The first occurred during the 10 minutes of emplacement of the debris avalanche when the levee constituting the South Fork Castle Creek blockage was deposited before the remainder of the avalanche had come to rest. Ground vibrations associated with avalanche emplacement were considerable (Stephen Malone, oral commun., 1983); it is conceivable that the blockage was subjected to accelerations on the order of 0.1 g for several minutes. The second occurred from 1140 to 1730 P.d.t. on the same day, when numerous shocks associated with the Plinian eruption of Mount St. Helens produced strong shaking. The blockage was subjected to peak accelerations of order 0.05 to 0.1 g (Stephen Malone, oral commun., 1983). Finally, the Elk Lake earthquake of February 14, 1981, could have produced peak accelerations at the blockage of 0.2 g for several cycles.

The effect of these events on the debris-avalanche deposit has not been studied, but it is presumed that the ground vibrations produced compaction of the deposit and increased its relative density. Ground-water levels in the blockage at the time of these shaking events were probably lower than those measured in September 1983.

DYNAMIC SLOPE-STABILITY ANALYSIS

STABL 3 contains an optional program that allows determination of the approximate effect of an earthquake on F_s ; this program was used to determine F_s values at all the cross sections previously tested for static stability, for two levels of earthquakes. In using this program, the assumption is made that dynamic loading from an earthquake can be replaced by a static horizontal force that is obtained from the product of the weight of the potential sliding mass and a seismic coefficient, n_s . Under this assumption, the section may be unstable if F_s approaches 1.0, but there is no theoretical basis to support this. Among other things, the value of n_s varies directly with earthquake magnitude, and two values of n_s were used in the analysis, 0.2 g and 0.4 g. As will be discussed subsequently, the larger value is believed to correspond closely to the seismic coefficient for the maximum credible earthquake for the SHZ. The maximum credible earthquake is believed to be near, but greater than, magnitude 6.0.

Modeled Cross Sections and Assumptions

F_s values were determined for all cross sections for seismic coefficients equal to 0.2 and 0.4 g and for water levels at their September 1983 positions. In addition, values of F_s were determined for cross sections CD, CF, CE, and BB for the range in seismic coefficients indicated above and for ground-water levels 25 feet above their September 1983 configuration, and finally for the water table at land surface. Wet and saturated unit weights of 105 and 125 lb/ft³, respectively, were assumed in all analyses. For all analyses, zero cohesion and a drained friction angle of 35 degrees were used with additional assumptions, the same as previously discussed under "Static Analysis."

Calculation of n_s

Methods of assigning seismic coefficient values include selecting an empirical value, assuming rigid-body response or using viscoelastic-response analysis. Because the last method provides a more rational approach, it was used to estimate a value for n_s that could be assigned to the blockage for the maximum credible earthquake along the SHZ. The value was obtained from the relationship:

$$\bar{n}_s(t) = \frac{1}{W} \sum m(y) \ddot{u}_a(y) , \quad (1)$$

where W is weight of sliding mass, m is an incremental horizontal slice of the mass, and $\ddot{u}_a$ is the absolute acceleration at each instant, t , under consideration; y is the vertical coordinate direction (Seed and Martin, 1966). It is necessary to specify boundaries of the sliding mass in order to compute average seismic coefficients, leading to a different value of average seismic coefficient for each potential mass at any instant of time. The matter is simplified by representing each sliding mass as a triangular wedge, thus permitting the average seismic coefficient over a given depth to be computed directly. For given values of embankment shear-wave velocity, damping factor, and embankment height, values of $\bar{n}_s(t)$ can be computed for any particular ground motion record.

For the September 1983 case, the blockage is assumed homogeneous, with a shear-wave velocity of 1,000 ft/s and 20-percent critical damping. The north-south component of the 1940 El Centro earthquake, with duration of 0 seconds, is assumed for analysis, with the peak acceleration scaled to 0.55 g. Calculations presented by Seed and Martin (1966) then allow direct estimation of seismic parameters. Seismic coefficients thus determined vary considerably as a function of time (Seed and Martin, 1966, with ordinate values multiplied by 1.70). For September 1983 purposes the variation in seismic coefficients is approximated by an equivalent number of acceleration cycles of constant amplitude. The fundamental period of the blockage foundation system is about 0.5 second at cross section DF. An equivalent seismic force series might be approximated by 10 cycles of force with a predominant frequency of 1.8 cycles per second, giving, to one significant figure, the following amplitudes of average seismic coefficient $\bar{n}_s(t)$: 0.6 g (for potential slide masses in the upper quarter of blockage), 0.5 g (for the upper half), 0.4 g (for upper three-quarters or full blockage height).

Thus, average seismic coefficients vary considerably with position in the blockage material, as well as with time, and higher values occur with increasing altitude. This is significant, because it influences the position of the most critical failure surface.

Results of Dynamic Slope-Stability Analysis

General results of all the dynamic analyses indicate that for a given position of the water table increasing earthquake magnitudes cause F_s and F_s^* values to decrease and potential failure surfaces to penetrate deeper into the blockage than they do in the results of the static analysis. All cross sections on the blockage, including those that were stable for all positions of the water table under static analysis, become unstable during shaking induced by earthquakes near the maximum credible value, even for September 1983 water levels. In addition, for an earthquake of given magnitude, rising ground-water levels cause F_s and F_s^* values to decrease, and in some cases cause potential failure surfaces to penetrate deeper into the blockage. Decrease in values of F_s and F_s^* as a result of increasing earthquake magnitude and ground-water levels is shown in figure 16. Each zone shown in the figure represents a given water-level condition and is bounded by the maximum and minimum F_s values for the 10 surfaces predicted by the model for each analysis. In addition to decreasing, the range in values for the 10 low F_s surfaces also narrows considerably.

Reduction in F_s and F_s^* values caused by increasing earthquake magnitudes and by increasing ground-water levels is significant. Table 4 shows this reduction for both conditions, and as can be seen, values of F_s^* fall below unity along many sections for higher n_s values and (or) higher ground-water levels. F_s^* values are below unity for all sections except GG' for $n_s = 0.49$ g, regardless of the position of the water table. They are also below unity for water levels 25 feet higher than in September 1983 and $n_s = 0.2$ g on all cross sections tested for this set of conditions. Narrowing of the range of the 10 low F_s surfaces shown in figure 16, combined with the reductions in F_s and F_s^* , indicates that larger areas of the blockage become potentially unstable as earthquake magnitudes and ground-water levels increase.

Deformation over the entire blockage is possible if an earthquake with a magnitude near 6.0 occurred with water levels at their September 1983 position. Critical failure surfaces at all cross sections except AA' extend below lake level, with the deepest extending approximately 120 feet below lake level and 100 feet behind the crest of the blockage. The model does not predict that any of these initial failures would result in immediate lake breakout, because even if slippage occurred simultaneously from the crest toward the lake and from the crest toward Castle Creek, a part of the blockage would remain intact and above lake level.

If a smaller earthquake ($n_s = 0.2$ g) occurred with water levels at their September 1983 position, considerable deformation of the blockage is also possible. The model predicts potential failure surfaces at all sections except GG', where F_s^* is 1.7. Greatest potential instability occurs along cross section DF, where potential failure surfaces reach their maximum depth below lake level (fig. 23). Once again, however, the model does not predict immediate breakout because simultaneous movement on both the upstream and downstream parts of the blockage still leaves a section of the blockage intact and above lake level. Retrogressive analysis of this remaining section, using the same assumptions that were used for static conditions, suggests that after a series of three successive, highly mobile failures on both sides of the blockage, the crest would be lowered below lake level and the lake could be released. The same results occur when retrogressive analysis is conducted on the section remaining after an earthquake near magnitude 6.0.

Model analysis predicts that some part of the blockage would remain intact and above lake level for all positions of the water table tested and for all magnitudes of earthquakes up to the maximum credible. Although large masses of blockage material are predicted to move, the altitude of the blockage crest would remain the same under the worst conditions analyzed—the water table at land surface, a maximum credible earthquake, and simultaneous slippage from the crest toward the lake and from the crest toward Castle Creek along the deepest potential failure surfaces. Retrogressive failure analysis on the remaining sections, however, predicts lake breakout in all cases.

Displacement of Sliding Masses

The preceeding analyses have indicated that retrogressive slope failure could result in lake breakout for static conditions when the blockage is saturated and for dynamic forces when water levels are at their September 1983 position or higher. As was discussed for static conditions, however, the degree of mobility required for the sliding masses during retrogressive failure is considered unlikely.

The possible displacements associated with slope failure were estimated on the basis of concepts outlined by Newmark (1965). Calculations were based on the assumption that the sliding mass moves as a coherent body and resistance is initiated along the failure surface. An earthquake with a square acceleration pulse of 0.1 to 0.2 second duration and 0.5 g amplitude was assumed, the latter value corresponding to the average seismic coefficient produced by the maximum credible earthquake in the upper one-half of the blockage. Displacements were calculated for single pulses and for the sum of 10 pulses and are plotted against the seismic coefficient of $F_s = 1$ (fig. 24). Displacements shown in figure 24 probably overestimate actual displacement for the assumed condition because pulses in opposite directions are ignored and because the value of seismic coefficients required for $F_s = 1$ decreases with displacement.

Figure 16 shows values of F_s versus n_s for selected positions of the water table, and can be used in conjunction with figure 24 to determine approximate displacement of a sliding mass along a given cross section for the assumed conditions. The value of n_s when F_s is equal to 1.0 can be selected from figure 16 for various positions of the water table. This value can then be used in figure 24 to determine an approximate displacement value for slippage along a failure surface. Slide displacements for these conditions are summarized in table 5. F_s values, and therefore seismic coefficients shown in figure 16, were obtained from model analysis that assumed drained strength and are therefore not necessarily conservative. Displacements shown in table 5 are only on the order of 5 feet or less for all cross sections for the September 1983 position of the water table. As a result, lake breakout from retrogressive failure following slope failure induced by an earthquake is considered to be highly improbable.

As the water table rises to 25 feet above September 1983 levels, the analysis suggest displacements up to several tens of feet on cross sections CE and CF, but less than 6 feet elsewhere. For fully saturated conditions, large displacements of sliding masses are possible at CE and CF because the F_s of many trial surfaces drops well below unity even for static conditions. These displacements cannot be estimated from the above analysis, but it is doubtful that movement would exceed 100 feet. Elsewhere, for fully saturated conditions, displacements of sliding masses of about 15 feet are indicated for sections BB' and CD. The type of deformation expected along DF, if the maximum credible earthquake occurs when the blockage is fully saturated, is shown in figure 25.

Seismic forces thus increase the possibility of deep-seated movements, and as ground-water levels rise, the likelihood of potential for displacement associated with a given earthquake increases. Displacements that would exceed several tens of feet are possible along sections CE and CF from either static forces or seismic shaking when water levels are at land surface. At other locations, however, predicted displacements are only several tens of feet or less, even for the maximum credible earthquake. The magnitude of these displacements suggests that the possibility of lake breakout indicated by retrogressive model analysis is probably remote for all positions of the water table for earthquakes equal to or less than the maximum credible earthquake for the area.

TABLE 4.--Model predicted factors of safety (F_s) against slope failure for selected cross sections, South Fork Castle Creek Blockage

<u>Profiles 0 = 35</u>			
<u>Experiment number</u>	<u>Assumed cohesion (lbs/ft²)</u>	<u>Assumed ground-water table</u>	<u>F_s</u>
<u>Cross-Section AA'</u>			
1	0	June 1982	2.1
2	0	+25 ft	1.6
3	0	at land surface	0.8
4	200	June 1982	2.4
5	200	+25 ft	1.9
6	200	at land surface	1.1
<u>Cross-Section BB'</u>			
7	0	June 1982	2.2
8	0	+25 ft	1.8
9	0	at land surface	1.4
10	200	June 1982	2.4
11	200	+25 ft	2.0
12	200	at land surface	1.6
<u>Cross-Section CD</u>			
13	0	June 1982	2.1
14	0	+25 ft	1.6
15	0	at land surface	1.3
16	200	June 1982	2.3
17	200	+25 ft	1.9
18	200	at land surface	1.5
<u>Cross-Section CE</u>			
19	0	June 1982	1.7
20	0	+25 ft	1.2
21	0	at land surface	0.8
22	200	June 1982	1.9
23	200	+25 ft	1.4
24	200	at land surface	1.0

TABLE 4.--Model predicted factors of safety (F_s) against slope failure for selected cross sections, South Fork Castle Creek Blockage--Continued

<u>Profiles 0 = 35</u>			
<u>Experi- ment number</u>	<u>Assumed cohesion (lbs/ft²)</u>	<u>Assumed ground-water table</u>	<u>F_s</u>
<u>Cross-Section CF - Lakeside</u>			
31	0	June 1982	1.6
32	0	+25 ft	1.1
33	0	at land surface	0.6
34	200	June 1982	2.0
35	200	+25 ft	1.5
36	200	at land surface	1.0
<u>Cross-Section GG'</u>			
25	0	June 1982	4.1
26	0	+25 ft	3.0
27	0	at land surface	2.4
28	200	June 1982	4.3
29	200	+25 ft	3.6
30	200	at land surface	2.8

TABLE 5.--Estimated displacement of sliding masses for selected positions of the water table at South Fork Castle Creek blockage

Cross section	Water-table position	n_s for $F_s=1$	Displacement, in feet	
			1 pulse	10 pulses
AA'	Sept. 1983 level	0.31	0.1 to 0.2	0.5 to 2
BB'	Sept. 1983 level	.23	0.1 to 0.4	1 to 4
	At land surface	.10	0.3 to 1	3 to 13
CD	Sept. 1983 level	.22	0.1 to 0.4	1 to 4
	Sept. 1983 level plus 25 feet	.17	0.2 to 0.7	2 to 6
	At land surface	.09	0.4 to 2	4 to 15
CE	Sept. 1983 level	.24	0.1 to 0.3	1 to 3
	Sept. 1983 level plus 25 feet	.08	0.4 to 2	4 to 17
	At land surface	<0	*	*
CF	Sept. 1983 level	.20	0.1 to 0.5	1 to 5
	Sept. 1983 level plus 25 feet	.05	0.7 to 3	7 to 29
	At land surface	<0	*	*
GG'	Sept. 1983	.43	0.02 to 0.1	0.2 to 1

*Unstable under static forces.

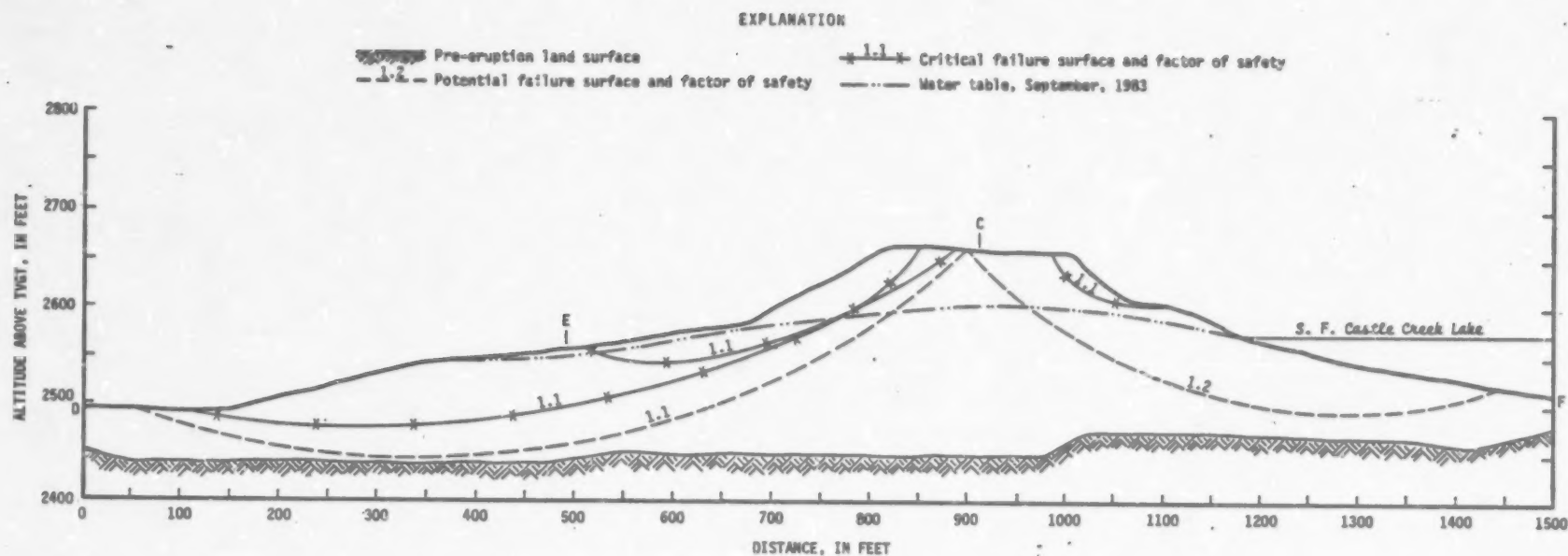


FIGURE 23.--Critical surfaces and potential failure surfaces encompassing the largest sections of the blockage for cross sections CD, CE, and CF with a seismic coefficient of 0.2 g, September 1983 water level, and zero cohesion.

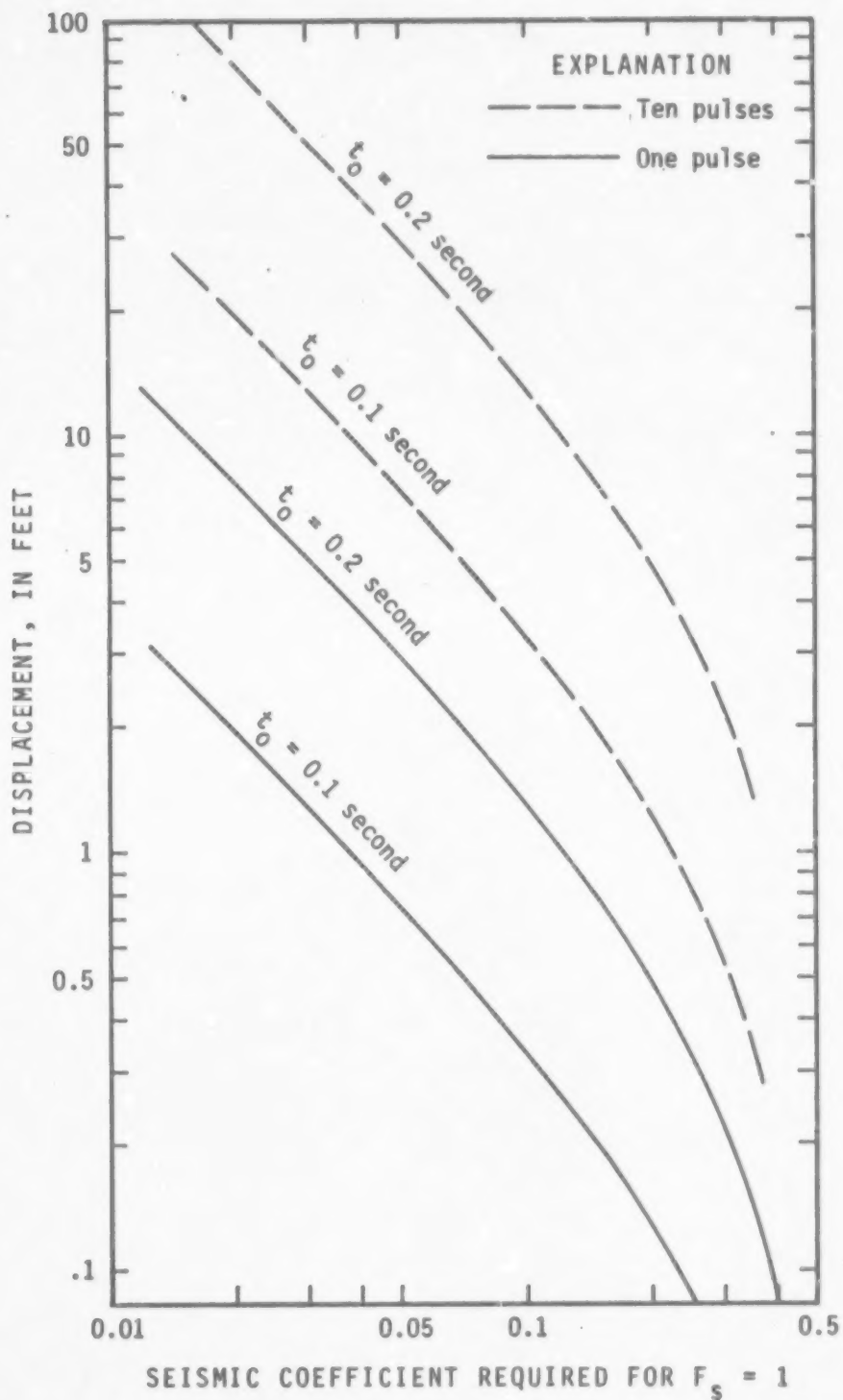


FIGURE 24.--Estimated displacement in the blockage resulting from an earthquake with an acceleration pulse of 0.5 g and duration of 0.1 and 0.2 seconds.

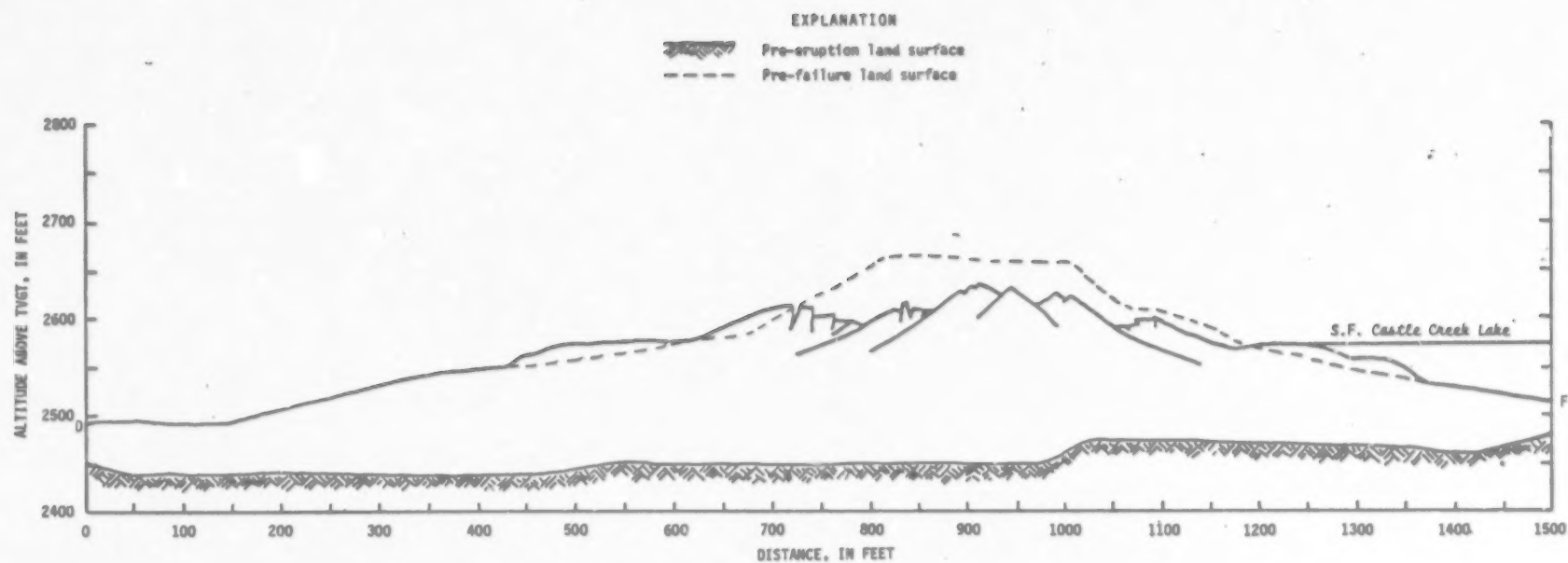


FIGURE 25.--Schematic of deformation expected with high ground-water level and maximum credible earthquake.

CONCLUSIONS

South Fork Castle Creek, a tributary to the North Fork Toutle River, was blocked by the debris-avalanche deposit associated with the May 18, 1980, eruption of Mount St. Helens. A lake that eventually reached a volume of 19,000 acre-feet formed behind the blockage and now poses a flood hazard of unknown magnitude to downstream areas if the blockage fails. The blockage has steep slopes and consists of the unsorted and unstratified debris-avalanche deposit that ranges in size from silt and clay particles to blocks tens of feet in diameter. The St. Helens seismic zone, which is believed capable of producing an earthquake larger than 5.5 but probably less than 7.0 magnitude, passes within a few miles of the blockage. The blockage has been subjected to three historic periods of shaking, with accelerations of 0.1 or 0.2 g. These events are presumed to have caused compactions of the blockage, increasing its relative density, and should have increased the resistance of the blockage to liquefaction (Mori and others, 1978).

Unit-weight and relative-density tests suggest that the deposit at South Fork Castle Creek is moderately compacted, and is probably typical of the Mount St. Helens debris-avalanche deposit in this respect. Unfortunately, the available data are fragmentary. Further attention should therefore be given to this issue, because of its relevance to questions of liquefaction and slide mobility and to strength/pore pressure/deformation behavior as estimated by laboratory tests on material compacted to field density.

Stability of the blockage relies heavily on ground-water conditions: as ground-water levels rise, stability of the blockage decreases. Ground-water levels were first measured in the blockage in September 1983. Depth to water below the crest of the blockage ranged from about 20 to 60 feet at that time. Water levels are believed to have been near their seasonal low in September 1983, and they could also potentially increase on an annual basis for several more years. Potential failure of the blockage from gravitational forces and from horizontal forces induced by an earthquake was evaluated for water levels at their September 1983 position and higher, including saturation of the blockage. In general, results of these analyses indicate that if an earthquake with seismic coefficient one-half that of the maximum credible occurred with water levels at their September 1983 position, substantial deformation could occur on the blockage. Slope failures could occur from the crest toward the lake and from the crest toward Castle Creek. Potential failure surfaces are deep, extending as much as 120 feet below lake level. A nearby earthquake with magnitude near 6.0 could cause much more extensive deformation on the blockage. As ground-water levels rise, the factor of safety for critical failure surfaces decreases and potential displacement associated with a given earthquake increases. As a result, potential deformation on the blockage also increases.

Slope failure from gravitational forces presents no significant problem unless the blockage becomes nearly saturated, although some deformation of the blockage is possible at lower ground-water levels. With the blockage fully saturated, slope failures extending as much as 30 feet below lake level could occur. From the crest toward the lake and from the crest toward Castle Creek, there is a potential for deep-seated surfaces along which sliding could occur.

None of the analyses for static or dynamic slope failure indicate that immediate lake breakout would result from initial slope failures on the blockage, even if they occurred simultaneously on both sides of the blockage. Only when retrogressive failure is assumed using highly mobile sliding masses does the possibility of lake breakout result. For lake breakout to occur as a result of retrogressive failure, displacements along slippage faces would have to be on the order of hundreds to thousands of feet, whereas actual displacements would probably be on the order of tens of feet under the worst conditions analyzed.

None of the analyses indicated the potential for a breakout of South Fork Castle Creek Lake as a result of initial slope failures on the blockage because some part of the blockage would remain intact and above lake level for all possible positions of the water table and for earthquakes up to the maximum credible magnitude for the area. Retrogressive failure in the remaining section of the blockage could lead to lake breakout if an earthquake with a seismic coefficient in the blockage of 0.2 g occurred when ground water was at existing (September 1983) levels or higher. Retrogressive failure could also lead to lake breakout following initial slope failures induced by gravitational forces with the water table at land surface. The assumptions used in the analysis for retrogressive failures are so conservative, however, that the possibility of actual lake breakout from slope failure is considered remote.

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